Effect of climate and soil water status on Cabernet Sauvignon (*Vitis vinifera* L.) grapevines in the Swartland region with special reference to sugar loading and anthocyanin biosynthesis

by

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Declaration

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Summary

Cabernet Sauvignon, the most planted red wine cultivar in South Africa, is prone to vigorous growth with low yields. The aim of the study was to describe how Cabernet Sauvignon grapevines react to climate and irrigation within the Swartland region. Such knowledge would assist growers in decisions regarding long term as well as short term cultivation practices. This study was part of a larger project carried out by the Infruitec-Nietvoorbij institute of the Agricultural Research Council at Stellenbosch to determine effects of soil type and climate on yield and wine quality of Cabernet Sauvignon. The larger project was carried out in selected grape growing regions, *i.e.* Stellenbosch, Swartland, Lower Olifants River and Lower Orange River.

Due to the proximity to the Atlantic Ocean, the study area in the Swartland region could be divided into two climatic regions for viticulture. Grapevines near Philadelphia closer to the ocean experienced less water constraints compared to those further inland near Wellington. Variation in stem water potential could also be related to soil water matric potential. Climate tended to have a more pronounced effect on the grapevine response to water constraints further inland than closer to the ocean. Vegetative growth, berry size and yield depended on water constraints experienced by the grapevines. In the warmer climate, severe constraints reduced yield.

In the warmer climate, grapes started to ripen earlier than those in the cooler climate. Sugar concentration (mg/mL) was highest where grapevines experienced moderate water constraints. These seemingly balanced grapevines had the highest sugar accumulation, probably due to optimum photosynthesis and carbohydrate utilization. Low water constraints increased vegetative growth which could have been a sink for sugar loading. In addition to sugar loading, degree Balling (˚B) increases could also have been due to a concentration effect where water constraints reduced berry volume. Therefore, ˚B is probably not a representative indicator of grapevine functioning.

Anthocyanin biosynthesis, as quantified on a per berry basis, showed that sugar and anthocyanin could be co-regulated, with anthocyanin biosynthesis reaching a plateau when the sugar content per berry reached 200 mg/mL to 220 mg/mL. At véraison, the most intense grape colour occurred where grapevines experienced moderate water constraints, *i.e.* single drip line at Wellington and no irrigation at Philadelphia. However, at harvest grapes from the cooler climate tended to have more intense colour and higher phenolics, indicating that lower temperatures favoured anthocyanin biosynthesis. These results supported earlier findings that grapevine water status influences berry volume and dynamics of berry ripening.

Water constraints tended to increase sensorial wine colour intensity, as well as wine fullness. Moderate water constraints at both localities resulted in the best sensorial wine quality. Yet there were indications that too severe water constraints could be detrimental to wine quality.

Irrigation can be used to manipulate grapevine growth in warmer climates, but might be less effective in cooler climates. In warmer climates, moderate water constraints required to achieve balanced grapevine functioning can be obtained with single drip irrigation, but this might not be the case in cooler climates.

Opsomming

Cabernet Sauvignon, die mees aangeplante rooiwynkultivar in Suid-Afrika, is geneig tot kragtige groei met lae opbrengste. Die doelwit van hierdie studie was om te beskryf hoe Cabernet Sauvignon-wingerdstokke reageer op klimaat en besproeiing in die Swartland-streek. Hierdie kennis sal kwekers help wanneer hulle besluite moet neem oor langtermyn sowel as korttermyn verbouingspraktyke. Hierdie studie was deel van 'n groter projek deur die Infruitec-Nietvoorbij Instituut van die Landbounavorsingsraad op Stellenbosch om die effekte van grondtipe en klimaat op die opbrengs en wynkwaliteit van Cabernet Sauvignon te bepaal. Die groter projek is in geselekteerde wingerdverbouingstreke uitgevoer, nl. Stellenbosch, Swartland, Benede Olifantsrivier en Benede Oranjerivier.

As gevolg van die nabyheid daarvan aan die Atlantiese Oseaan kon die studiegebied in die Swartland-streek in twee klimaatstreke vir wingerdbou verdeel word. Wingerdstokke by Philadelphia, wat nader aan die oseaan is, het minder waterstremming ervaar as dié verder binnelands naby Wellington. Veranderinge in stamwaterpotensiaal hou moontlik ook verband met die grondwater- matrikspotensiaal. Klimaat het 'n groter effek op die reaksie van die wingerdstok op waterstremming verder binnelands as nader aan die oseaan. Vegetatiewe groei, korrelgrootte en opbrengs was afhanklik van die waterstremminge wat deur die wingerdstokke ervaar is. In die warmer klimaat het die ernstige stremminge opbrengs verminder.

In die warmer klimaat begin druiwe vroeër ryp word as in die koeler klimaat. Suikerkonsentrasie (mg/ml) was die hoogste waar wingerde matige waterstremming ervaar het. Hierdie skynbaar gebalanseerde wingerdstokke het die hoogste suikerakkumulasie vertoon, moontlik as gevolg van optimum fotosintese en koolhidraatverbruik. Lae waterstremming het vegetatiewe groei verhoog, wat ook 'n vraagpunt vir suikerlading kon wees. Benewens suikerlading kon verhogings in grade Balling (˚B) ook moontlik aan 'n konsentrasie-effek toegeskryf word in terme waarvan waterstremming die korrelvolume verminder het. ˚B is dus moontlik nie 'n verteenwoordigende indikator van wingerdstokfunksionering nie.

Antosianienbiosintese, soos gekwantifiseer op 'n per-korrel basis, het getoon dat suiker en antosianien saam gereguleer kon word, en dat antosianienbiosintese 'n plato bereik het wanneer die suikerinhoud per korrel 200 mg/mL tot 220 mg/mL was. By deurslaan het die mees intense druifkleur voorgekom waar die wingerdstokke matige waterstremming ervaar het, d.w.s. enkel druplyn op Wellington en geen besproeiing op Philadelphia. Teen oes was die druiwe in die koeler klimate egter geneig om meer intense kleur en meer fenole te bevat, wat aandui dat laer temperature antosianienbiosintese bevoordeel. Hierdie resultate ondersteun vroeër bevindings dat die waterstatus van die wingerdstok 'n invloed op korrelvolume en die dinamika van korrelrypwording het.

Waterstremming neig om die sensoriese wynkleurintensiteit te verhoog, asook die volheid van die wyn. Matige waterstremming op beide liggings het aanleiding gegee tot die

beste sensoriese wynkwaliteit. Tog was daar aanduidings dat waterstremming wat te straf was, nadelig kon wees vir wynkwaliteit. Besproeiing kan gebruik word om wingerdgroei in warmer klimate te manipuleer, maar is moontlik minder effektief in koeler klimate. In warmer klimate kan die matige waterstremming wat benodig is vir gebalanseerde wingerdstokfunksionering, verkry word deur enkel drupbesproeiing, maar dit is moontlik nie die geval in koeler klimate nie.

This thesis is dedicated to my heavenly Father and all those who loved, supported and encouraged me through the process of this study.

Biographical sketch

Tara Olivia Mehmel was born on 27 May 1985 in Cape Town, lived her first and best ten years of her life on a farm in the Karoo, that is where she discovered her love and need for open space and wildlife. She moved to a farm in Cape Town, there birthed the love for the wine lands. She attended Somerset House and Somerset College in the winelands, matriculated in 2003. She obtained her BSc-degree in 2007 from the University of Stellenbosch, majoring in Viticulture and Oenology. In 2008 she obtained her HonsBScAgric-degree in Viticulture at the same University. In December 2007 Tara started her field work for her MScAgric-degree in Viticulture at the University of Stellenbosch and the ARC Infruitec-Nietvoorbij.

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Preface

This thesis is presented as a compilation of six chapters. Each chapter is introduced separately and is written according to the style of the journal the South African Journal of Oenology and Viticulture.

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Chapter 1

INTRODUCTION AND PROJECT AIMS

INTRODUCTION AND PROJECT AIMS

1.1 INTRODUCTION

All the grapevine cultivars that are grown in South Africa belong to the *Vitis vinifera* species that was originally imported from Europe. About 75 cultivars have been approved for production of Wines of Origin (WO). Each cultivar has specific growing condition for the production of optimal quality fruit expressing the unique characteristic of the specific cultivar. Therefore, there is a close interactive relationship between cultivar, origin and wine. The origin of the wine is important. There are a host of environmental factors which could potentially affect grape berry composition by altering the rate and timing of biosynthetic pathways which govern the accumulation and degradation of phenolics. The range of external factors like climate, soil, geography, trellis system, management and soil water status tend to modify grapevine growth parameters such as vegetative growth, flower initiation, set and yield. These external factors also alter the physiology of the grape berry to change its composition and therefore final wine quality.

The pronounced diversity in South Africa's vineyard and wine landscapes is considered an asset and demarcation of areas of origin is rated highly important by the industry (WOSA). The Western Cape falls into the warmer wine growing regions, yet it is influenced by the two oceans, namely the Atlantic and Pacific Ocean. There is also great diversity of topography which, along with the ocean, affects meso climatic conditions which have a prominent influence on viticulture. Due to factors influencing the diversity of wine growing regions, wine producers are focused on identifying and selecting the best sites for optimal ripening of a specific cultivar and desired wine style. The Coastal region of the Western Cape includes the WO districts Paarl, Tygerberg, Swartland, Darling, Stellenbosch and Cape Point. The Swartland WO, in the western part of the larger Cape wine growing region, is a large area with the land under vineyards still being significantly lower than other wine growing regions in the Western Cape. This is attributed to the land traditionally being used for growing wheat. The diversity of terroir is, however, suitable for the production of a varied range of wine. The average annual rainfall in the Swartland region is marginal (300 mm to 500 mm per year), with 30 to 40% falling during the growing season. The temperature of this region is classified as a Class V, which is a hot to very hot region (Le Roux, 1974; Winkler *et al.,* 1974). The climate is warm and dry, with average mean temperatures ranging from 25˚C to 35˚C over the ripening season. The general cultivation practiced in this region is bush grapevines, due to the marginal rainfall and high temperatures. The region has also earned a name for a variety of fortified and dessert wines. The WO wards of this study are Wellington which falls into the Paarl district, and Philadelphia which is in the Tygerberg district. As these two wards are on the outer limits (close to the sea and inland) of the Swartland district, they are considered to be part of the

Swartland district due to the selected locality of the site for this study. Therefore, for the purpose of this study the two localities near Wellington and Philadelphia are considered to fall into the Swartland region.

Climate is described in viticulture on three levels, namely macro climate describing the region, meso climate describing the vineyard locality and micro climate describing the grapevine environment. The traditional wine growing areas along the coastal zone are rarely more than 50 km from the ocean and experience beneficial coastal conditions like sea breezes. In the Western Cape, there is a significant contrast between the Cool Ocean and warm inland temperatures. The cool coastal conditions are due to the occurrence of sea breezes, especially during the maturation period in February and March (Bonnardot, *et al.,* 2001). The temperate climate of the Western Cape features warm summers and cool winters, with rainfall between May and August. The main effects of sea breeze mechanism during February in the Stellenbosch region in South Africa consists of, firstly, a change in wind direction and increase in velocity in the early afternoon, secondly, higher relative humidity closer to the ocean that decreases rapidly further inland, thirdly, smaller temperature fluctuations near the coast compared to inland day and night temperatures and lastly, the maximum temperature was reached earlier in the day near the coast compared to inland (Bonnardot *et al.,* 2001). Temperature plays an important role in determining wine quality (Le Roux, 1974; De Villiers *et al.,* 1996) and the mean February temperature is used amongst other climatic indices to demarcate the most suitable locality for a specific cultivar. Temperature influences almost every aspect of grapevine functioning, influencing photosynthesis, anthocyanin biosynthesis and other important biochemical functioning required for optimal grape quality. Optimum temperature for anthocyanin biosynthesis is between 30ºC and 35ºC (Spayd *et al*., 2002). The climatic conditions of a vintage can influence grape quality through the amount of insolation, temperature and water balance (Van Leeuwen *et al.,* 2004).

Soil of the Cape wine regions are highly varied due to the large differences in topography and geology which significantly impact the meso climate and grapevine performance. Soil and rooting depths, as well as soil texture, play an important part in soil water holding capacity (Greenspan, 2005). Soil water holding capacity, particularly under non-irrigated conditions would exhibit a prominent influence on Cabernet Sauvignon wine style in South Africa (Conradie, 2002). Soil may influence grapevine development and fruit ripening through mineral supply and water holding capacity. The most suitable for Cabernet Sauvignon were those where water constraints resulted in earlier shoot growth slackening, reduced berry size and high sugar and anthocyanin content thereby increase the wine quality potential (Van Leeuwen *et al.,* 2004). Soil may affect moisture and nutrient availability to the grapevine, due to water constraints limiting or inducing canopy growth and due to the soils heat retaining and light reflecting properties. Soil structure also has a significant effect on root growth due to its penetrability.

The effect of climate and soil on grapevine development and grape composition can be explained via their influence on plant water status (Van Leeuwen *et al.,* 2004). Grapevine water status depends on the climatic conditions and the soil water holding capacity. Many studies indicate that moderate water constraints have positive impact on the grapevine functioning and final wine quality (Choné *et al*., 2001 and Van Leeuwen *et al.,* 2004). It is well known that irrigation influences yield, must composition and final wine quality in other countries (Chapman *et al.,* 2005), as well as in South Africa (Myburgh & Howell, 2006; Myburgh, 2006).

Cabernet Sauvignon, a hybrid cross of Cabernet franc and Sauvignon blanc, is originally from Bordeaux region of France. It is an increasingly significant variety in the Western Cape, known for producing top-class wines. In general, red varieties account for 44% of the national vineyards and the most widely planted varietal is Cabernet Sauvignon, accounting for 13% of the total (WOSA). Cabernet Sauvignon is a vigorous, late ripening cultivar, with small berries and bunches and known as a low yielding cultivar (De Villiers, 1986). Due to the cultivar’s susceptibility to low yields, it is important to find an optimum balance between yield and wine quality. Herbaceous, green bell pepper or earthy aroma is unique of Cabernet Sauvignon and other typical but less prominent flavours are mint, eucalyptus and blackberries. These aromas develop well with age into spicy, full, complex wines.

1.2 PROJECT AIMS

The study in the Swartland region is part of a project carried out by ARC Infruitec-Nietvoorbij in Stellenbosch to determine the effects of atmospheric conditions and soil water holding capacity on grapevine water status, yield and wine quality of Cabernet Sauvignon. The ARC project has been carried out in different grape growing regions of South Africa, *i.e.* in the Olifants River, lower Orange River and Stellenbosch regions. This study directly explores two sites, one within the Wellington ward and the other within the Philadelphia ward in the Swartland region, where temperature, soil water status and grapevine water status varied due to the climatic variation, soil water holding capacity and the volume of water received.

Since climate and soil type have an effect on the production and wine quality of Cabernet Sauvignon vineyards in the Swartland region. A range of grape samples will represent large variation in 1) grapevine water status due the soil water status and environment, 2) sugar loading rate and concentration and 3) anthocyanin biosynthesis. In addition, the hypothesis is also formulated that sugar loading and anthocyanin biosynthesis are corregulated and are influenced by the distance from the Atlantic ocean and the soil water holding capacity.

The primary objectives of the study were to assess (A) the climatic influence caused by distance from the Atlantic Ocean, effecting the grape and wine quality parameters and (B) the effect of soil water holding capacity on the grapevine and wine quality, according to the sugar loading, anthocyanin profile and sensory evaluation of Cabernet Sauvignon grapevines at different localities in the Swartland region by determining: (i) Climatic conditions during two growing season; (ii) Root characteristics and soil water status; (iii) Grapevine water status; (iv) Grapevine vegetative characteristics; (v) Grapevine berry characteristics; (vi) Sugar loading; (vii) Anthocyanin biosynthesis and (viii) Sensorial wine style and quality.

1.3 LITERATURE CITED

Bonnardot, V., Carey, V., Planchon, O. & Cautenet, S. (2001). Sea breeze mechanism and observations of its effects in the Stellenbosch wine producing area. *Wineland*, October 2001, 107-113.

Chapman, D.W., Roby, G., Ebeler, S., Guinard, J-X & Matthews, M.A. (2005). Sensory attributes of Cabernet Sauvignon wines made from grapevines with different water status. *Austr. J. Grape & Wine Research* **11**, 339-347.

Choné, X., Van Leeuwen, C., Dubourdieu, D. & Gaudillers, J.P. (2001). Stem water potential is a sentative indicator of grapevine water status. *Annals of Botany* **87**, 477-483.

Conradie, K. (2002). Grondvorm kan wynstyl grootliks beïnvloed: Cabernet Sauvignon uit Durbanville en Robertson. *Wineland*, November 2002, 107-109.

De Villiers, F. S. (1986). Wine grape cultivars: Cabernet Sauvignon. VORI 159/1986. Farming in South Africa.

De Villiers, F.S., Schmidt, A., Theron, J.C.D. & Taljaard, R. (1996). Onderverdeling van die Wes-Kaapse wynbougebiede volgens bestaande klimaatskriteria. *Wynboer*, January 1996, T10-T12.

Greenspan, M. (2005). Integrated irrigation of California winegrapes. *Practical Vineyard & Winery*, March/April 2005, **79**, 21-43.

Le Roux, E. G., (1974). n Klimaatsindeling van die Suidwes-Kaaplandse Wynbougebiede. M.Sc.-Tesis, Univ. Stellenbosch, 7600 Stellenbosch.

Myburgh, P.A. & Howell, C.L. (2006). Water relations of *Vitis vinifera* L. cv. Sunred Seedless in response to soil water depletion before harvest. *S. Afr. J. Enol. Vitic.* **27** (2), 196-200.

Myburgh, P. (2006). Irrigation management with particular reference to wine quality - a brief overview of South African research. *Wynboer Technical Yearbook* 2006, 50-53.

Spayd, S., J. Tarara, D. Mee, and J. Ferguson.(2002). Seperation of sunlight and temperature effects on the composition of *Vitis vinifera cv.* Merlot berries*. Am. J. Enol. Vitic.* **53**,171-182.

SAWIS. (2007). Production areas &maps as on 30 November 2007.

http://www.sawis.co.za/cert/productionareas.php

http://www.wine-searcher.com/regions-swartland

Van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S. & Dubourdieu, D. (2004). Influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic*. **55** (3), 207-217.

Winkler, A. J., Cook, J. A., Kliewer, W .M. & Lider, L. A., (1974). General Viticulture. *Univ. Calif*.

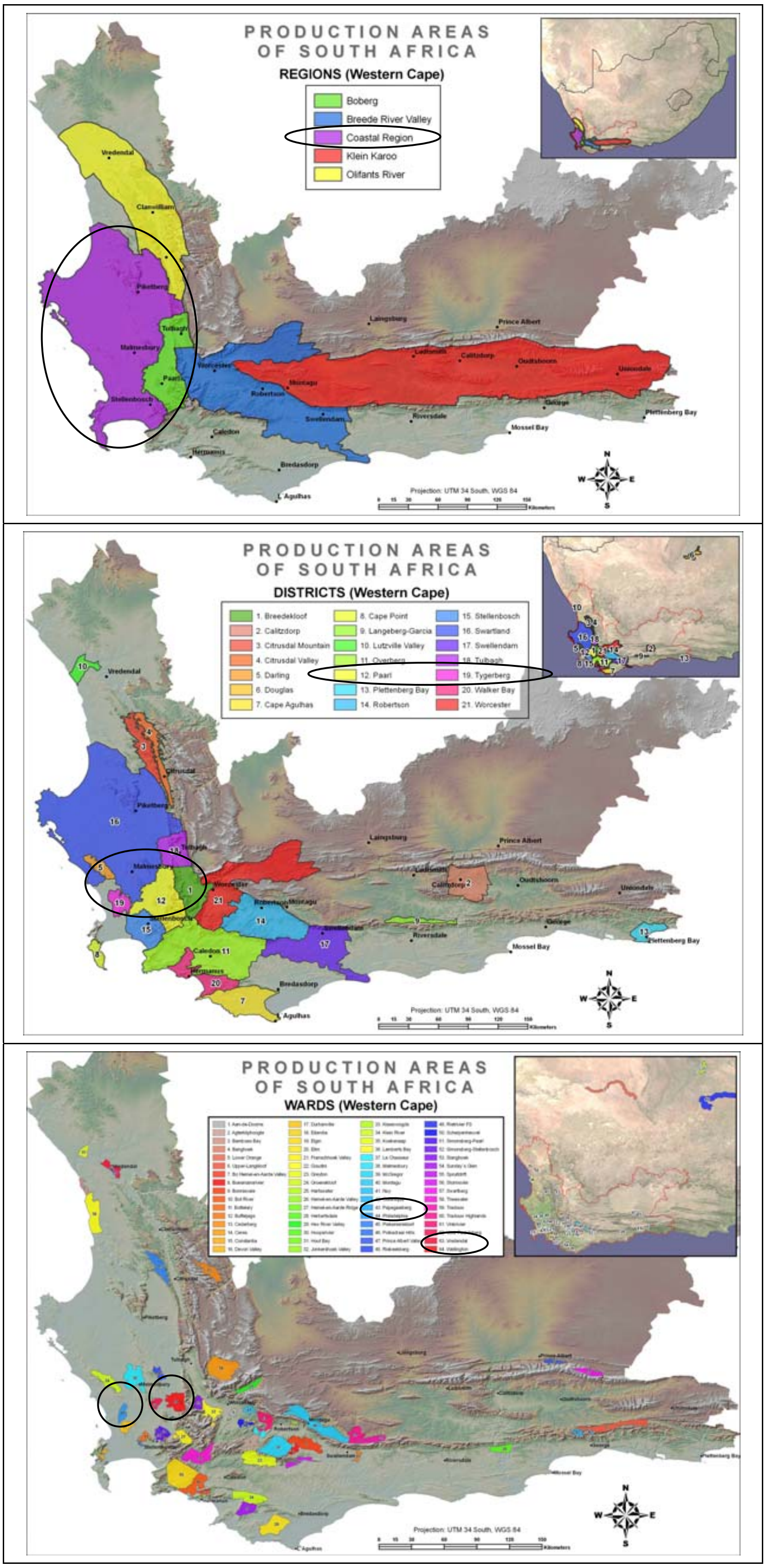

Figure 1. Regions, districts and wards of the Western Cape wine production area. The circled areas relates to the Swartland region and the general localities of the study area. (**http://www.sawis.co.za/cert/productionareas.php**)

Chapter 2

LITERATURE REVIEW

The effect of climate and grapevine water status on production and wine quality of Cabernet Sauvignon (*Vitis Vinifera* L.)

CHAPTER 2

2.1 INTRODUCTION

In grape production the need always exists to find a balance between yield, which is important for economic viability of the grower and wine quality, which is important in the increasing competitive world markets. Grapevine physiology, grape and wine quality, are affected directly and indirectly by water stress, which may vary according to soil type and prevailing climate. Temperature, relative humidity and exposure to wind, as well as soil related factors, influence grapevine growth and wine quality for Cabernet Sauvignon and other cultivars (Deloire *et al.,* 2005). Terroir relies on the relation between climate, soil and grapevine, also considering viticulture and enological sciences and techniques necessary to ensure wine quality (Deloire *et al.,* 2005). Grapevine water status and the biochemical evolution in the grape berry from set onwards, are important for the understanding of the terroir role with respect to quality of the harvest and wine style. Water stress can have positive and detrimental effects on grape production and wine quality. However, on the other hand, over irrigation will nearly always be detrimental to wine quality.

The wine producing regions of South Africa are characterized by many diverse climates, from Mediterranean to semi arid, therein each climate type, there are many diverse soil forms with different water holding capacities (Carey *et al.,* 2004). The Western Cape region is classified as having hot, dry summers. The most important characteristic of soil is its capacity to supply sufficient water to the grapevine during the entire growing season. The significance of the viticultural environment for wine style and wine quality in South Africa has long been recognized (Le Roux, 1974; Carey *et al.,* 2008; Bonnardot *et al*., 2001). The aim of this chapter is to discuss the terroir concept and effects of grapevine water status on production and wine quality of Cabernet Sauvignon.

2.2 THE TERROIR CONCEPT

Terroir has been acknowledged as an important factor in wine quality. It can be defined as an interactive ecosystem, in a given place, including climate, soil, and the grapevine (rootstock and cultivar) (Van Leeuwen *et al.,* 2004). The effects of soil water and nitrogen status linked to the soil type have been shown in studies on Cabernet Sauvignon and Merlot (Choné *et al.,* 2001). The effects of climate, soil and cultivar have been found to be highly significant with regard to grapevine behavior and berry composition, with the greatest effect seen to be climate and soil and their influence mediated through grapevine water status (Van Leeuwen *et al.,* 2004). The climatic conditions of the vintage can influence grape quality through the amount of insolation, temperature or water balance (rainfall-k*ET (mm)) (Van Leeuwen *et al.,* 2004; Smart 1985). Climate is also important for the choice of grapevine varieties, as each variety requires a minimum temperature summation to reach maturity (Deloire *et al.,* 2005). The best terroir expression is obtained when grapevine varieties suit the climate, therefore reaching complete ripeness at the end of the season. When early ripening grape varieties are planted in warm climates not suited to their growth, aromatic expressions and wine quality is reduced due to the ripening being too fast. In contrast, late ripening cultivars planted in cool climates will not reach optimal maturity, resulting in lower wine quality that will have the tendency to be more vegetative in aromatic character.

2.2.1 CLIMATE

In viticulture, climate is described on three levels, namely macro climate on a regional scale, meso climate on a site scale and micro climate in the canopy (Smart, 1985; Deloire *et al.,* 2005). Macro climate describes the climate of a wide area or region over a long period using annual, seasonal and monthly data (Deloire *et al.,* 2005). Meso climate is more site specific due to differences in altitude, slope inclination, aspect and distance from large bodies of water and is used to describe the climate of a specific vineyard. Meso climate is described using daily and hourly data from shorter periods of time. Recent studies have emphasized the important effects of meso climate, especially for marginal growing conditions (Smart, 1985). Micro climate is the climate closely surrounding and therein the grapevine canopy. Canopy micro climate is influenced by the vigour of the grapevine (Deloire *et al.,* 2005). Canopy temperature is directly influenced by the amount and distribution of leaf area and its interaction with the above ground climate and soil surface characteristics. The minutes and seconds climatic data recorded is used to describe the micro climate.

Climatic indices, namely temperature, rainfall, relative humidity, sunshine duration and water balance, are combined components that are used to describe the viticultural potential of a region on a macro scale (Deloire *et al.,* 2005). Carey, (2001) noted that some classifications are for global application, such as by Smart & Dry (1980), Huglin (1978), Gladstones (1992) and Tonietto (1999). Subsequent adaptations have made them applicable to specific countries, such as South Africa (Le Roux, 1974; De Villiers *et al.,* 1996), or regions (Amerine & Winkler, 1944). Long term weather data, e.g. mean February temperature (MFT), is used as a criterion to determine wine quality potential of a specific region (De Villiers *et al.*, 1996; Myburgh, 2005a&b). Mean February temperature is based on the concept of Smart & Dry (1980) and was adapted by De Villiers *et al.* (1996). De Villiers and colleagues (1996) divided the South Western Cape into different climatic regions according to MFT. February is the warmest month in many parts of the Western Cape and it is the month during which the majority of the grapes ripen. One of the most well known temperature indices for viticulture is that of the growing degree days (GDD), as first suggested by Amerine & Winkler (1944) for California (hereafter referred to as the Winkler index). Le Roux (1974) applied the heat summation technique to the Western Cape wine producing regions and adapted the growing season and classification to make it relevant for South African conditions. The growing season is from 1st September to 30th March and is calculated as a summation of the daily mean temperature above 10˚C.

The heliothermal index (HI) is used worldwide to describe the potential of a region for viticulture (Huglin, 1978). This index is based on the mean and maximum monthly temperatures from October to March (Huglin, 1978; Tonietto & Carbonneau, 2004). The calculation incorporates a coefficient to allow for the greater photosynthetic active radiation that occurs with longer days at higher altitudes. A coefficient of 1 is used for the South Western Cape (latitude 34˚ South). This index provides information regarding the level of heliothermal potential. It provides a better indication of the sugar loading potential according to the varieties, rather than the classic temperature summations, thereby providing qualitative information (Tonietto & Carbonneau, 2004). A good discrimination of the region's climate with regard to global heliothermal conditions during the vegetative cycle of grapevine and cool night conditions during the ripening period can be obtained when HI is used in conjunction with cool night index (CI) (Tonietto & Carbonneau, 2004). The CI is the night coolness variable and is quantified using the mean night temperature during the month preceding harvest (Tonietto & Carbonneau, 2004). The month used is generally March, as many of the red cultivars ripen in March. This index is used to determine the qualitative potential of wine growing regions with respect to wine colour and aroma, notably in relation to secondary metabolites (polyphenols and aromas) in grapes.

2.2.2 SOIL

Soil is an important element in the constitution of a given terroir (Deloire *et al*., 2004), for the development of soil maps. It is therefore of cardinal importance to understand the soil grapevine relationship through the soil and root profile (Deloire *et al.,* 2005). Soil may influence grapevine development and fruit ripening through mineral supply and water holding capacity. Mineral nutrient uptake by the grapevine from the soil and the ability of the soil to provide these nutrients did not appear to have a significant impact on the fruit quality (Van Leeuwen *et al*., 2004). It has been shown that petiole magnesium (Mg), potassium (K), nitrogen (N) is dependent on soil type and, to a lesser extent on vintage. However, in the study of Van Leeuwen *et al*. (2004), no link could be established between soil and petiole N, P, K and Mg content. Significant correlations were, however, found for petiole and juice K content and petiole Mg content and berry sugar content. Soil determines how the root system develops and the depth to which the grapevine roots will grow (Deloire *et al.,* 2004). Available soil water depends on rainfall, runoff water, planting density and the training system which determines the surface area of foliage per area (Deloire *et al*., 2004). In the Van Leeuwen *et al.* (2004) study, the sandy soil included a water table within reach of the roots. Even in the dry vintages, grapevines on this soil type did not experience water constraints or stress. However, gravelly soil has a lower water holding capacity, therefore water constraints can be severe. The clayey soil was subjected to early but moderate water deficit due to the better water holding capacity. It is clear that the intensity of grapevine water deficit stress depends not only on climate, but also on the water holding capacity of the soil.

2.2.3 CABERNET SAUVIGNON IN RELATION TO TERROIR

Currently, Cabernet Sauvignon is the cultivar that is planted second most in South Africa. This cultivar can be cultivated in moderate climatic regions with medium textured soils, inducing moderate plant stress (WOSA). Cabernet Sauvignon (Petit Cabernet, Petit Vedure) is a heavy complex wine with an intense colour and remarkable maturation potential. Environmental parameters such as climate (rainfall, relative humidity, air temperature, soil temperature, direction and intensity of dominant winds), topography (slope, exposition, sunlight exposure and landscape form) and soil (mineralogy, compaction, granulometry, soil water reserve, depth, and colour) have an overriding effect on the performance of Cabernet Sauvignon grapevines (Carey *et al.,* 2008). In addition, vintage, soil and topographic related site characteristics and scion clone affected the phenology, growth, yield, berry composition and wine related parameters of Cabernet Sauvignon grapevines (Carey *et al*., 2008).

Cool ripening seasons result in wines with less intense but more complex aromas. Wines with poor colour and a green vegetative character are sometimes the outcome of cool regions. Warmer regions produce good wines with intense aromas, but not as complex as those grown in moderate climates. The warmer regions produce wines that are thin and have coarse tannin structure with little fruit aromas (Buttrose *et al.,* 1971). Cabernet Sauvignon grapevines have a good tolerance for heat, and in fact prefer hotter ripening periods complemented by cooler night temperature for optimal development of quality and colour. Whole plant and berry levels integrate the environment of the grapevine, there is a direct relationship with the quality of the harvest product and the final quality of the wines (Deloire *et al.,* 2005).

2.3 VINEYARD WATER REQUIREMENTS

Water loss in the grapevine is a combination of plant transpiration and soil evaporation (Deloire *et al.,* 2004). Water requirements are defined as the total amount of water, regardless of its source, required by crops for normal growth under field conditions (Myburgh, 1998). Evapotranspiration (ET) can be defined as the combined water loss as evaporation from the soil surface and transpiration from the plants from a given area and during a specific period of time (Laker, 2004). The dynamics of evaporation and transpiration are controlled by environmental and soil surface conditions, as well as viticultural aspects (Myburgh, 1998), therefore ET changes between vineyards. Factors that affect the soil water status, soil surface conditions and transpiration of grapevines and soil characteristics will all affect the ET of the vineyard (Van Zyl, 1975; Smart & Coombe, 1983; Myburgh 1998). Transpiration and evaporation are regarded as a combined variable of ET in research on grapevine water requirements and irrigation.

2.3.1 EVAPORATION

Evaporation from the soil surface is one of the major processes responsible for water loss in cropped lands (Laker, 2004 and references therein). It is largely influenced by variations in tillage and irrigation practices and heterogeneity of the soil, resulting in a considerable difference in evaporation between localities (Myburgh, 1998). More water will evaporate on a warm, windy day than on a cool, windless day (Myburgh, 1998), as it is assumed that the wind has a more prominent effect on evaporation compared to other factors such as shading from the canopy. Shading of the soil surface by the grapevine canopy reduced the evaporation, but the effect diminished as the soil dried out (Myburgh, 1998). Evaporation can be reduced by minimal cultivation practices such as applying a mulch, either directly by adding cover material like wheat straw (Myburgh, 1998), or indirectly by cultivating a cover crop which acts as mulch when it is killed later in season (Fourie *et al.,* 2001). Water is conserved by mulching, especially when frequent water is received either by rain or irrigation (Myburgh, 1998; Van Huyssteen *et al.,* 1984).

2.3.2 TRANSPIRATION

Evapotranspiration consists primarily of soil water extraction by the grapevine via transpiration (Myburgh, 1998). Transpiration is quantified by means of stomatal conductance, which is strongly affected by the prevailing atmospheric conditions such as temperature, radiation and water saturation deficit of the atmosphere (Düring & Loveys, 1982). Sap flow rate may vary according to climatic regions. The positive effects of higher stomatal conductance can be lost by a lower evaporative demand under temperate conditions (Myburgh, 1998). Sap flow tends to be erratic during the day due to the changes in the canopy micro climate, thereby influencing grapevine transpiration. Transpiration is therefore affected by viticultural and atmospheric conditions (Myburgh, 1998). Sap flow rates during the night, attributed to the replenishment of water deficits during the day, were substantially lower compared to the rate measured in full sunshine, and the sap flow tended to increase with increasing leaf area (Myburgh, 1998). Myburgh (1998) suggested that the strong relationship between sap flow and leaf area proved that transpiration was closely related to total leaf area per grapevine and that the ET increases with an increase in leaf area of the grapevine.

2.3.3 EVAPOTRANSPIRATION

Grapevines do not distinguish between different sources of water. These sources of water can be from precipitation, irrigation and stored soil water (Van Zyl & Van Huyssteen, 1984). Soil type, cultivar and viticultural practices affect the irrigation requirement, with climate regarded as the dominating factor (Van Zyl & Van Huyssteen, 1984). A study conducted by Van Zyl & Weber (1981) indicated that a total seasonal requirement of 500 mm water, from bud burst to harvest, appeared to be adequate for economically viable viticulture in the coastal region of the Western Cape. Depending on the soil type, the stored winter rain provides for most of the water required by the grapevines during the ripening season in cooler regions. However, due to the low rainfall received in some South African wine growing regions where the soil water is limited, irrigation has to be applied. Van Zyl & Weber (1981) conducted an experiment on the effect of supplementary irrigation on plant and soil moisture relationships in the Stellenbosch region. They showed that all the plant available water was already depleted in January, causing the grapevines to show severe water stress earlier as the water content of the upper soil horizons had reached wilting point. However, more favourable soil water content was obtained with irrigation compared to non-irrigated plots. When the soil water is readily available throughout the profile, ET is determined mainly by the climatic condition. In contrast, when the soil available water is lower, ET is determined by soil resistance to moisture movement (Van Zyl & Weber, 1981). Evapotranspiration values were much lower for non-irrigated grapevines compared to irrigated grapevines. Evapotranspiration, and thus the crop coefficients, decreased after the drying of the soil surface (Van Zyl & Weber, 1981). Drier soil and higher evaporative demand causes stronger suction from the leaf with the suction being expressed in units of pressure (Greenspan, 2005).

2.4 GRAPEVINE WATER STATUS

Plant water status is explained in terms of the water supply (soil) together with the demand (canopy architecture, evaporative demand). Previous studies emphasised the importance of the water status of the plant and the bunch micro climate with relation to the biochemistry and berry growth and ripening (Deloire *et al.,* 2005 and references therein). Many studies indicate the positive impact of moderate water stress on phenolic compound synthesis and grape quality (Van Leeuwen & Seguin 1994; Ojeda *et al.,* 2002). Van Leeuwen *et al*. (2004) obtained optimum quality of grapes in vintages with low summer rainfall which led to water deficit stress in two seasons. The intensity of grapevine water deficit stress depends not only on the climatic parameters but also on the water holding capacity of the soil (Van Leeuwen *et al.,* 2004). The stomatal regulation is strongly determined by its sensitivity to air humidity (Winkel & Rambal, 1993). Midday stomatal control helps to prevent xylem cavitations during the hours when the grapevine is exposed to high evaporative demand. The increased water use efficiency of the grapevine promotes root growth. Therefore, stomatal regulation is a powerful mechanism, assuring high conductivity of water through the entire plant (Winkel & Rambal, 1993).

The grapevine is the best indicator of the plant water status. The pressure chamber method is one of the most widely used methods of monitoring grapevine water status

(Scholander *et al.,* 1965; Greenspan, 2005). This method estimates the capacity of the plant to retain water by pressuring a leaf with neutral gas and taking a reading in kPa when water comes out of the petiole. The less free water available in the plant, the more pressure will be required to cause liquid to exude (Deloire *et al.,* 2005). Leaf water (Ψ_L) potential has gained wide acceptance as a fundamental measure of plant water status and has been widely applied in viticulture research (Smart & Coombe, 1983). Shortly before dawn (predawn), Ψ_L approaches equilibrium with soil water potential and reaches a maximum daily value. After this, Ψ_L rapidly decreases to attain a minimum value at/after midday, followed by a gradual recovery during the late afternoon and night (Smart & Coombe, 1983).

Predawn leaf water potential (Ψ_{PD}) is determined before sunrise when the stomata of the grapevine are closed and therefore the leaves are in equilibrium with the soil moisture layer (Williams & Araujo, 2002; Deloire *et al.,* 2004). Threshold values for ψ_{PD} have been established, making it possible to evaluate the degree of water deficit in the grapevine. The thresholds are: 0 MPa to -0.2 MPa (no deficit), -0.2 MPa to -0.4 MPa (mild to moderate deficit), -0.4 MPa to -0.6 MPa (moderate to severe deficit) and -0.6 MPa to -0.8 MPa (severe to high deficit) (Carbonneau *et al*., 1998). At different phenological stages of grapevine growth, grapevines respond differently to the plant water status. Should the plant water status be maintained between the threshold of 0 to -0.2 MPa (no deficit), from budburst to maturity, it causes unfavourable condition due to excessive vigour and dilution of berry metabolites. However, during the period from bud burst to flowering, these conditions of no water deficit are favourable inducing normal growth. The threshold values of -0.2 to -0.4 MPa (mild to moderate deficit) from flowering to véraison provides favourable ripening conditions, as the constraint slows vegetative and fruit growth controlling excessive vigour, yet no disruption of biochemistry of the grapevine. In contrast, if the Ψ_{PD} levels are between -0.4 to -0.6 MPa (moderate to severe deficit), unfavourable growth conditions are created, as the vegetative growth slows, there is a reduction in photosynthesis and yellowing of leaves in the bunch zone, an inhibition of berry growth and tannin biosynthesis. Water status of -0.4 to ≤ -0.6 MPa (moderate to severe and progressive) from véraison to maturity creates favourable growth conditions, with growth reduction, reduced sugar loading in berries when favourable amount are reached for alcohol strength, stimulation of anthocyanin biosynthesis, slow ripening without inhibition and increase in skin to flesh ratio. When the plant water status is less than - 0.6 MPa (severe and drastic) during the period from véraison to maturity, the plant is too stressed, unfavourable conditions for ripening with possible inhibition of ripening, severe growth reduction, reduction of sugar loading and disruption of anthocyanin biosynthesis (Deloire *et al.,* 2004).

Predawn leaf water potential is a very reliable method used to determine grapevine water status and can be used for the characterisation of homogeneity or heterogeneity in the vineyard in relation to the water status of the soil. However, Ψ_{PD} can underestimate the grapevine water status during the sunshine hours when the soil water content is heterogeneous from the daily interaction with the environment (Améglio *et al*., 1999). This is especially seen after small amounts of rain or irrigation on dry soil, as the water deficit is underestimated the day following the water application (Deloire *et al*., 2005). Predawn leaf water potential better reflected the soil water availability compared to Ψ_L, and detected the onset of water stress in the grapevines earlier and more accurately than Ψ_L (Williams & Ajauro, 2002). Therefore, Ψ_{PD} gave a good estimation of the soil water status in the vineyards. This method enables the measurement of short term hydric response of the plant in reaction to change in soil water status (Deloire *et al.,* 2005). Integrating the season with Ψ_{PD} qualifies the degree of water stress experienced by the grapevine (Lopes *et al.,* 2001).

Predawn leaf water potential measurements done at regular intervals in the season provides an evolution of the water status of the grapevine during the growing season. This provides important information of the impact of water status on the growth of the plant and the ripening of the berry (Deloire *et al*., 2005). Deloire *et al.* (2003) showed that a moderate stress level maintained at Ψ_{PD} of -0.2 MPa to -0.4 MPa during set and véraison and -0.4 MPa to -0.6 MPa from véraison to harvest was favourable water constraints for balanced grapevine functioning. Leaf water potential has been used to monitor the water relations of the grapevines and has been correlated with various aspects of grapevine physiology, vegetative growth and yield (Williams & Araujo., 2002).

Leaf water potential is frequently used to determine the daily dynamic of plant water use (Carbonneau *et al.,* 2004). Hunter & Myburgh (2001) state that Ψ_L is insensitive to the soil water status and should therefore be used in conjunction with soil water measurements. Greenspan (2005) suggested that any Ψ_L measurement should be done together with the visual monitoring of water status by the grapevine growth response. When the midday Ψ_L is greater than -0.8 MPa, there is active shoot growth and tendrils reach past the growing tip. When Ψ_L is between -0.9 MPa to -1.0 MPa, there is slowed active growth, tendrils are even with the growing tip and basal tendrils are still turgid. When ψ_L ranges from -1.2 MPa to -1.3 MPa, active growth ceases and leaves extend beyond the growing tip and basal tendrils started to droop. Finally, a Ψ_L of -1.4 MPa to -1.5 MPa results in dead or missing shoot tips and drooping basal tendril and leaf petiole angle becomes smaller. The stress classes as described by Greenspan (2005) are: no stress experienced by the grapevine (Ψ_L greater than -1.0 MPa); mild stress (-1.0 MPa < Ψ_L< -1.2 MPa); moderate stress (-1.2 MPa < Ψ_L < -1.4 MPa); high stress (-1.4 MPa < Ψ_L < -1.6 MPa) and severe stress (Ψ_L greater than -1.5 MPa).

Stem water potential (Ψ_S) is the most discriminating indicator of moderate and severe stress when compared to Ψ_{PD} and Ψ_L. Stem water potential is measured on leaves that are bagged with aluminium foil that is lined with a plastic sheet at least an hour before the measurement. This measurement normally takes place midday, when the values reach a minimum. Bagging prevents transpiration, so the leaves can reach equilibrium with the water potential in the stem. The Ψ_S values are highly correlated with transpiration (Choné *et al.,* 2001). Stem water potential has been shown to be linearly correlated with applied water and soil water availability (Williams & Araujo, 2002), therefore Ψ_S is less variable and able to detect small but significant differences between treatments. Stem water potential is a way of obtaining whole grapevine water status during the day (Deloire *et al*., 2005).

Changes in the conductance of the plants’ water pathways are the only mechanism by which the plant can achieve homeostasis in internal water status. The question that arises is, what strategy plants can develop to partially avoid exposure to water stress. This refers to the temporal variations of the plant water status, which is characterised by two major cycles. Firstly, a daily cycle with maximum evaporative demand near solar noon and secondly, an annual cycle with maximum water stress occurring during summer drought in temperate and Mediterranean climates. The grapevines’ response takes place at two different levels when the constraints are imposed on the plant by these two cycles (Winkel & Rambal, 1993). The first grapevine response is instantaneous control of transpirational flux via the stomata and secondly, the ability to survive drought periods of several weeks, which depends on the long term water relations between the plant and soil. The short term response is mainly related to solar radiation. The long term response is dependent on the crop development in response to the seasonal change of the environment (Winkel & Rambal, 1993). Water homeostasis has the adaptive significance as it enables the plant to perform well under water stress conditions, ensuring the maintenance of Ψ_L that is not detrimental to the carbon assimilation in the grapevine (Winkel & Rambal, 1993).

2.4.1 FACTORS AFFECTING GRAPEVINE WATER STATUS

There are three factors involved in the development of water stress that are affected by atmospheric and soil conditions, namely transpiration rate, rate of water movement from the soil to the roots and the relationship of soil water potential to Ψ_L (Kramer, 1983). There have been several studies done on the effect of water supply on grapevine functioning and grape quality (Bodin & Morlat, 2006). Regular but moderate water supply contributes to the best grape ripening and, to the contrary, severe water stress is detrimental to the grape and wine quality (Bodin & Morlat, 2006).

2.4.1.1 Atmospheric conditions

The soil water plant atmosphere continuum can be described as a water stream flowing from a source of limited capacity and variable potential to the atmosphere (Hillel, 1980). Stomatal opening is affected by water deficits and therefore used as an indicator of plant water stress. Environmental factors, namely light intensity, carbon dioxide (CO_2) concentration, hormones and atmospheric temperature affect the stomatal behaviour of the grapevine (Kramer, 1983). Increased water stress causes stomatal opening, transpiration and photosynthesis to decrease, therefore also decreasing the CO_2 uptake and fixation (Kramer, 1983). The most important atmospheric factors that affect grapevine water status are incoming solar radiation (insolation), temperature, vapour pressure deficit (VPD) and wind speed.

Radiation: Increased radiation, either by higher intensity or longer exposure, will increase temperature especially that of exposed leaves (Jackson & Lombard, 1993). Van Zyl (1987) found that the Ψ_L in sun exposed leaves was significantly lower compared to the shaded leaves during the middle part of the day. This confirmed that ψ_L correlated with leaf temperature and photosynthetically active radiation (PAR). Furthermore, stomatal conductance (g_s) decreased in the leaves during the middle of the day and increased again during the late afternoon. The stomata of unstressed grapevines were closed at midday, irrespective of the available water (Van Zyl, 1987). The light compensation point, *i.e.* where nett CO_2 exchange is zero, for grapevines is between 10 µmol quanta/m^2/s and 20 µmol quanta/m^2/s (Düring, 1988). The maximum stomatal opening has been recorded at a photosynthetic photon flux rate (PFD) of 130 to 300 for an individual leaf (Winkel & Rambal, 1990). Maximum canopy conductance is associated with maximum PFD which occurs when the greatest proportion of the canopy is exposed to direct solar radiation.

Temperature: One of the most important parameters affecting grapevine growth and development and which has an effect on almost every aspect of grapevine physiological functioning is temperature. Every facet of plant growth and development, each physical process, enzymatic reaction, membrane field, transport processes and phase transition is separately subjected to the influence of temperature (Coombe, 1987 and references therein). Temperature has also been acknowledged to have a major influence on the grape composition and quality (Coombe, 1987). Leaf water potential tends to correlate best with leaf temperature and optimum leaf temperature for photosynthesis is accepted to be above 25˚C and below 30˚C. In a study conducted by Van Zyl (1986), canopy temperature was showed to be significantly and linearly correlated with soil water content and that the onset of grapevine water stress occurred at plant available water contents of 30% to 60%. Canopy temperature increased up to 1.16˚C to 1.62˚C above the control plots (Van Zyl, 1986). When a plant lacks water its stomata closes principally due to a lack of turgidity in the guard cells. Transpiration and evaporative uptake of energy is hereby reduced, causing the leaf temperature to rise. The leaf temperature can therefore be used as an indicator of water stress (Van Zyl, 1986).

Vapour pressure deficit (VPD): Stomata are controlled by numerous environmental factors and in general, an increase in VPD above a certain threshold causes a reduction in g_s in most plant species, including *Vitis* species (Düring, 1987). However, the effect of VPD on g_s of grapevines is cultivar dependant. Stomatal conductance decreased as VPD increased throughout the day for grapevines receiving less than full vineyard evapotranspiration (ET_o). An increase of VPD from 1 to 3 kPa reduced the g_s by 50% for grapevines irrigated at 60% PAW and reduced the g_s by 75% for grapevines irrigated at 20%, determined by means of a weighing lysimeter (Williams *et al.,* 1994). The base line levels for when the plant experiences no water constraints are when the maximum Ψ_s values range from -0.5 to -1.0 MPa for the most extreme VPD values of -1 to -4 kPa (Olivo *et al.,* 2009). For control grapevines, when Ψ_s values were approximately -0.6 MPa, the effect of VPD was negligible, whereas for Ψ_s values of -0.8 MPa, the VPD effect was relevant (Olivo *et al.,* 2009). A decrease in g_s due an increase in VPD may be more pronounced in grapevines grown under drought conditions (Düring, 1976). The sensitivity of Ψ_S values to the VPD was found to be greater for water deficit treatments than control treatments, as the more negative Ψ_s values had a greater sensitivity to the VPD rather than the phonological effect due to plant water hydraulics (Olivo *et al.,* 2009). In semi arid environments, VPD and ambient temperatures are highly correlated.

The relationship between ambient temperatures and g_s is, therefore, similar to the relationship between VPD and g_s (Williams *et al.,* 1994)

Wind speed: Winds of 3 to 4 m/s can result in the closure of the stomata, thereby causing an inhibition of photosynthesis. Wind speed is of significant importance as it affects the heat and mass transfer of leaves and grapevine canopy in its entirety. High wind velocities can cause structural damage of plant tissue, whereas constant winds of low to medium velocities can cause disruption of physiological processes (Williams *et al.,* 1994). Wind affects the exchange of CO_2 and water vapour between the plant and atmosphere, causing stomatal closure and thereby limits CO_2 uptake, affecting photosynthesis, even in optimal available water conditions (Freeman *et al.,* 1982; Williams *et al.,* 1994). The degree to which the leaf net CO_2 assimilation rate is reduced by increased wind speed is dependent on the extent by which g_s is reduced. A study in the Loire Valley had shown that higher wind speeds in the period prior to harvest reduced must acidity, and especially malic acid levels in red cultivars (Carey *et al.,* 2008). Therefore, increased wind exposure was associated with wines having a higher wine pH.

2.4.1.2 Soil water status

The effect of soil type is the least understood natural factor with regard to wine quality (Saayman, 1992). The effects of climate and cultivar have been isolated and are understood to some degree, but the effect of the soil is confusing especially in warmer climates, as the climate tends to dominate all the soil factors (Fregoni, 1977). Soil water holding capacity and plant available water (PAW) are affected by soil depth, texture and structure. Field water capacity is at the upper limit of PAW, which is accepted as -0.01MPa, but can be reached at a lower soil water matric potential in the field (Van Zyl, 1981). The lower limit of PAW is -1.5 MPa and this is known as permanent wilting point, where plant roots are not able to absorb more water from soil, as the soil water is held at very high soil matric potentials (Van Zyl, 1981). It has been found that the soil water potential at field water capacity in the field can vary from as high as -0.005 MPa in sandy soils to as low as -0.050 MPa in clay soils (Myburgh, 1996). If the soil water potential decreases below a certain level, it is no longer able to supply the plant with water and water stress develops in the plant.

Predawn leaf water potential (Ψ_{PD}) is the most sensitive indicator of water stress in the grapevines and therefore gives an indication of availability of soil water to the grapevine. Predawn leaf water potential is highly correlated with soil water potential and water content, as the readings are taken when the plant is in equilibrium with the soil environment. In contrast, Ψ_L is affected by the soil environment but also the atmospheric conditions namely the VPD (Myburgh 2003a). Van Zyl (1987) found plant water stress to set in at a soil water potential of -0.064 MPa for grapevines. If soils do not have sufficient water holding capacity, irrigation is recommended, especially in grape growing areas like the Western Cape. This restriction of limited water can be overcome by aiming for optimal root densities by narrower plant densities for most efficient use of soil water (Archer *et al.,* 1988).

Deep, well drained soils with a reasonably high PAW holding capacity per unit soil depth, allows for a deep distribution of roots and therefore will buffer the grapevines against variations in the PAW status (Gladstones, 1992). The best vineyards are characterized by the ability to produce consistently good quality wine, even in seasons that are unfavourable for good quality wine. Studies have shown that grapevine water status tends to decrease with an increase in soil depth, with the optimal depth for soil preparation for vineyards being between 600mm and 1000mm. The factors that restrict the effective soil depth are fluctuating water tables, weathered or solid rock, excess salt, high pH, high sodium adsorption ratio and resultant unfavourable soil physical conditions (Van Zyl & Van Huyssteen, 1979). Water logging is another limiting factor restricting root distribution, therefore adequate drainage is important. When the soil water becomes limited, this results in prolonged periods of grapevine water stress.

2.5 GRAPEVINE RESPONSE TO WATER STATUS

Canopy management and its consequences on bunch exposure are determinant factors of berry composition and wine quality (Deloire & Hunter, 2005). The uniform distribution and height of the canopy are important factors impacting on grape and wine quality and lowering the heterogeneity in the yield, therefore the grapevine should be cultivated so that the canopy is sufficient and efficient.

2.5.1 VEGETATIVE PARAMETERS

There are many contradictory results on the effect of available water on all aspects of viticulture due to the difference in soils, and in particular, climate between localities. The growth of the root system depends on the water supply to the soil and on the training system which determines the volume of aerial parts of the plant in term of total and exposed foliar surface area (Deloire *et al*., 2004). Studies have shown that the rootstock variety differed significantly in terms of how the water status evolved after véraison, therefore confirming the ability of the rootstock to influence the water supply to the plant. This notably influenced the biochemistry of the berry, especially anthocyanin biosynthesis (Deloire *et al*., 2004).

Grapevine water status, in conjunction with the sum of temperatures over the growing period of the grapevine, affects the vegetative growth. The relationship between exposed or total foliar surface area and grape production is influenced by the grapevine water status (Deloire *et al.,* 2004). There is a relationship between the training system, root system and foliar surface area. This has an interactive effect in the drying out of the soil, therefore increasing the water stress of grapevines. Quantification of vigour and vegetative growth are important for the comparison of different situations such as comparing plots with different water relations (Deloire *et al.,* 2005).

A strong relationship exists between improved grape quality and water deficit before véraison, due to water deficit influencing the grape quality indirectly (Van Leeuwen *et al.,* 2004). A decrease in shoot growth is an indication of water stress in the grapevine, was shown by Van Zyl (1981). Myburgh (2003b) disclosed that irrigation at 90% PAW depletion level reduced vegetative growth significantly in comparison to irrigation at 30% depletion. Water deficit early in the season (before véraison) provokes early shoot growth cessation and reduces berry size. Under these conditions berry sugar, anthocyanin contents are increased because of the increased ripening speed, as well as the total acidity decreasing due to a decrease in malic acid content due to respiration (Van Leeuwen *et al.,* 2004).

The growing parts of the grapevine are primarily affected by water stress under different water status conditions. Excessive vigour due to too much water or N leads to overcrowding of leaves in the canopy, creating an unfavourable bunch micro climate for ripening (Deloire *et al.,* 2004). Moderate water stress retards shoot growth without notably affecting photosynthetic activity, facilitating the distribution of sugars in the berries during ripening (Wang *et al.,* 2003a&b). Principle shoot length is used to provide information on the dynamic of plant growth. The growth of the main and secondary shoots is directly linked to the plants N and plant water status (Deloire *et al.,* 2005).

2.5.2 REPRODUCTIVE PARAMETERS

2.5.2.1 Grape berry development

The growth of the grape berry consists of two successive sigmoid cycles, each with distinctive characteristics (Coombe, 1992). The first phase (berry set) is one of initial rapid growth with cell division and during the second phase (véraison) cell growth slows (lag phase) and berry colour changes as phenolics start to accumulate as the grape berry becomes a sink. The third phase is the second active growth phase. Cell expansion and ripening takes place during this phase to produce a phenologically ripe grape berry for harvest. One of the most important characteristics of the third phase is the rapid accumulation of phenolic pigments, which are secondary products of sugar accumulation (Coombe & McCarthy, 2000).

Coombe & McCarthy (2000) showed that the calculated berry volumes showed divergent double sigmoid time curve, with volume increasing till harvest. Water is the predominant determinant of berry volume and xylem sap, which dilutes aqueous organic ions and root derived organic metabolites, is the main source of water for the berries during the first growing cycle. At the beginning of the second growth cycle, when berries resume swelling, the flow of xylem sap into the berry is obstructed due to the stretching and breaking of the tracheids in the brush zone where the vascular bundles enter the berry. Berry growth would then depend mainly on the phloem sap, therefore showing the link between water and sugar increases during ripening and growth, as they are linked to the same source. Sugar is the predominant component of berry solutes. The primary control of accumulation of both solutes (sugar) and non solutes (water) was the unloading of the phloem sap into the berry (Coombe & McCarthy, 2000). Phloem transport becomes impeded once the berry weight reaches its maximum. The phenomena, of non solutes per berry decreasing while the solutes per berry stays constant is due to berry shrinkage, the continuation of water loss by transpiration. The timing of berry shrinkage is closely related to the timing of flowering rather than environmental factors causing grapevine stress (McCarthy, 1999). The blockage of the phloem occurs by deposits in the sieve tube area.

There are three stages of varying contributions of xylem and phloem translocation to water and solutes to the growing and ripening grape (Coombe & McCarthy, 2000). The first stage is from berry set to véraison and berry volume, which is determined by cell division in the pericarp, increases sigmoidally to the lag phase at which stage the berries are hard and green. The water for cell expansion is from the xylem and the phloem, and the principle solute accumulating is malate (increase in acid). The second stage is from véraison to 18-20 ˚B. This is the typical onset of ripening with the softening and expanding of the berries. Xylem flow is impeded and phloem is the only transport system. Water therefore moves into the berry flesh in the form of phloem sap along with sugars. Sugar and K accumulate in the skin cells along and, in addition to this, anthocyanins are biosynthesised. The third and final stage is from 18-20˚B till harvest and development at this stage differs between varieties. Coombe & McCarthy (2000) observed that Shiraz decreased in berry weight due to the blockage of phloem transport, so water and sugar supply to the berry is cut off. The decline in volume was due to transpiration from the berry with a subsequent increase in juice ˚B. At this stage, regardless of the impeded phloem transport, there is an accumulation of non-anthocyanin glucosides in the berries.

A study by Ojeda *et al.* (2001) showed that irrigation applied either early in the season, i.e. between anthesis and véraison or late, i.e. from véraison to harvest, significantly modified the weight, diameter and volume of grape berries through its influence on cell expansion. Berry growth is governed by water supply. Berry volume and sugar accumulation are affected by many factors, namely plant water status, photosynthetic activity and temperature (Wang *et al.,* 2003 a&b).

The ratio of exposed leaf area to yield affects the phloem sugar loading in the ripening berry (Wang *et al.,* 2003 a&b). Kliewer & Weaver (1971) found that a leaf area to fruit weight ratio up to 1.4 m^2/kg increased berry size, sugar and anthocyanin concentration. Grape quality was high on the soils that induced water deficit, especially on clayey soils where water deficit in the season are moderate due to the higher water holding capacity (Van Leeuwen *et al.,* 2004).

2.5.2.2 Yield

It has been reported that there is an increase in grape yield with regular water applications (Van Zyl & Weber, 1981). Growth and reproduction are affected by plant water status, which is a good indicator of the availability of soil water to the plant (Van Zyl & Weber 1981). Van Leeuwen *et al.* (2004) showed berry weight to be mainly influenced by soil type, followed by cultivar and berry sugar concentration depends mainly on the cultivar, soil type and vintage. Berry mass is not nearly as sensitive to moisture stress during the ripening period as during the cell division phase and berry size can be significantly reduced by water deficits induced after flowering. Recent studies have indicated that applied water stress between flowering and véraison does not modify cell division but rather cell enlargement in an irreversible manner, depending on the intensity and duration of stress induced (Deloire *et al*., 2005 and references therein). However, water deficits occurring between véraison and harvest have reversible affects on the berry. Water deficit modified the diameter of the berries, influencing the volume of the berry which will affect the ratio of skin surface to juice content, as well as the composition of the must and wine (Deloire *et al.,* 2004). The concentration and dilution phenomena are indirectly dependant on the plant water status, which is related to the soil water availability and evaporative demand. The number and size of cell in the grape berry are important factors influencing the ratio of skin surface to pulp, which affects the quality of harvest (Deloire *et al*., 2005).

2.5.3 JUICE COMPOSITION

The availability of soil water affects sugar concentration, titratable acidity, malic to tartaric acid ratio, colour of must, berry size, harvesting date and final wine quality. Van Leeuwen *et al.* (2004) showed that total acidity and pH of the grape juice is dependent on vintage, and to a lesser extent, on cultivar and soil type. Total acidity is mainly determined by the malate concentration, which is highly variable between vintages due to the temperature variations. Excessive (luxurious) water application during ripening stages stimulates unwanted vegetative growth, where the actively growing shoot utilise the carbohydrates to the detriment of the ripening berries. This results in less sugar loading into the berries, as well as there being less incentive for the production of sugar (Saayman, 1992). An over abundance of water or too little water available resulting in severe stress conditions, are both equally detrimental to the quality of the grapes at harvest. Sugar accumulation can be delayed by grapevine water stress, but mild water stress reduces the vegetative growth and can increase sugar accumulation (Smart & Coombe, 1983). The sugar loading in the berry depends on the grape variety and its interaction with the environmental conditions associated with grapevines water use and carbon supplies (Wang *et al.,* 2003 a). Water deficit reduces the photosynthetic activity of the grapevine, which in turn reduces the sugar loading.

Increased irrigation frequencies and volumes applied before the ripening period increased the total titratable acidity (TTA) (Van Zyl & Weber, 1977). Total titratable acidity decreased significantly in berries subjected to water stress during the first ripening phase of berry growth. The composition of the berry in terms of sugars, titratable acidity (tartaric and malic acid), phenolic compounds (tannins, proanthocyanins, flavonols, anthocyanins etc), is strongly dependant on the grapevine water status due to the indirect effect of the grapevine canopy affecting the micro climate of the bunch zone (Deloire *et al.,* 2004).

Water stress increased phenols in juice and skins, increased anthocyanins in skins and reduced malate and increased proline in juice. However, there was no effect on the onset of véraison or the duration of ripening (Matthews & Anderson, 1988). Smart & Coombe (1983) showed that excessive irrigation slows ripening; increases yield by berry enlargements, elevate juice pH and acid content and reduce anthocyanins as a result of shading by excessive shoot growth. On the other hand, water constraints, if not too severe, induces early ripening, reduces yield, berry weight and malic acid due too excessive exposure of the canopy. Grapevine water status can affect berry aroma composition as well as wine style and this effect may be indirect due to effects of water stress on vegetative growth and thus canopy structure (Carey *et al.,* 2004). Water constraints can have possible direct implications for the metabolic profile of the berry.

2.5.3.1 Sugar loading

Sugar loading is defined as the evolution of the quantity of sugar per berry, expressed in mg per berry, from véraison onwards. Grape berries begin to accumulate sugar from the moment they begin to soften at véraison (Coombe, 1992) and sugar phloem unloading is the first step in this accumulation of sugar. Sugar loading is a realistic indicator of the photo-assimilate quantity accumulating in the sink organ (Wang *et al.,* 2003a&b). The partitioning of photo assimilates in the plant is dependent on phloem loading at the source (mature leaves) and the phloem unloading at the sink (berry). There are many pathways for assimilate unloading. Wang *et al.* (2003b) explained one theory by means of an *in vivo* experiment system called the “berry-cup” technique. The “berry cup” technique was used to study and demonstrate the effects of water stress on sugar phloem unloading into ripening grape berries. Wang *et al.* (2003b) showed that glucose and fructose, in similar quantities, are the dominant sugars in the phloem unloading solution. The daily dynamics of sugar accumulation is the same for the normal and stressed grapevines during ripening, with the most active unloading occurring between 07:00 and 07:30, and lowest unloading in the afternoon. Phloem unloading occurs in parallel to the process of photosynthesis that is temperature and water sensitive. Phloem sugar unloading was greater in normally watered grapevines compared to water stress grapevines during ripening, because of the dynamic of photosynthesis which depends mainly on the grapevine water status (Wang *et al.,* 2003a). Sugar accumulation in berries depends on source sink and sink-sink relationships in the grapevine (Carbonneau & Deloire, 2001). The accumulation of sugar in the berry via the phloem unloading mechanism, depends on the photosynthetic activity of the grapevine and this is dependant on the water status of the grapevine throughout the day and during the ripening period (Wang *et al*., 2003a).

Water constraints have been shown to inhibit grapevine photosynthesis (mainly related to stomatal closure), plant growth, fruit size and yield (Schultz & Matthew, 1993; Greenspan *et al*.,1994; Wang *et al.,* 2003a). Water constraints affect the metabolism of primary and secondary compounds and their accumulation and transport to and into the berry. Therefore, water constraints have been shown to be a major factor influencing fruit quality (Wang *et al.,* 2003a). Berry volume and sugar accumulation are affected by plant water status, photosynthesis and temperature (Van Leeuwen *et al.,* 2004).

Sugar loading into the berry is coupled with the dynamics of sugar concentration changes and may be considered as a useful indicator of grape quality. Active sugar loading is calculated on the basis of berry volume and sugar concentration. The kinetic monitoring of the amount of sugar per berry is a viable method of measuring the plants physiological functioning, mainly related to photosynthesis which is a reliable indicator of the temperature that the grapevine is subjected to and grape grapevine water status (Hunter & Deloire, 2005; Wang *et al*., 2003a). The kinetics of sugar loading is distinguished by three principle sugar loading profiles. The first stage is that of a continual and rapid loading, which occurs from véraison with the plant sources actively functioning in producing carbon and supplying the sinks (berry and secondary shoots). The second stage is that of a slow sugar loading. There is an inhibition of ripening with lower sugar content per berry and there can be blocked ripening, which could be caused by an imbalance in the grapevine, or excessive water constraints or crop load in relation to the exposed leaves (Carbonneau & Deloire, 2001). Lastly, sugar loading reaches a plateau phase where the active sugar loading to the berry from the previous two stages is the cessation of sugar loading. The plateau is reached when the sugar loading is less than 3 mg per berry per day. Once the plateau of sugar loading has been reached, the evolution of ripening depends on other factors, namely cultivar, bunch microclimate, leaf to fruit balance, ratio of primary to secondary shoots and the climate during berry ripening (A. Deloire personal communication).

2.5.3.2 Anthocyanin biosynthesis

High sunlight stimulates berry anthocyanin biosynthesis (Smart, 1985; Bergvist *et al.,* 2001; Spayd *et al.,* 2002; Downey *et al.,* 2004). The optimum temperature range for anthocyanin biosynthesis is between 30˚C and 35˚C (Spayd *et al.,* 2002). High temperatures reduce anthocyanin biosynthesis (Joscelyne *et al.,* 2007; Downey *et al* 2006). Temperature has also been acknowledged to have a major influence on the grape composition and quality (Coombe, 1987). There is a significant effect of vintage and soil type on berry anthocyanin content and it is not determined by cultivar (Van Leeuwen *et al.,* 2004). The composition of the grape berry changes dramatically during ripening, anthocyanin biosynthesis starts at véraison and is correlated with increased sugar content (Kennedy*,* 2002).

The increase in anthocyanin content in grape berries subjected to water deficit is a common phenomenon, as the biosynthesis of pigments in the berry is a response to environmental and climatic factors such as temperature, light, partial defoliation, training system, soil characteristics and N availability (Ojeda *et al.,* 2002). Ojeda *et al.* (2002) confirmed that berry size influences phenolic content and proved that anthocyanin biosynthesis in the berries can be limited by intense water deficit applied during the period between anthesis and véraison (green growth stage). The phenol content was directly dependant on the total skin to flesh ratio, which was affected by water deficit, especially when applied during the green growth stage of the berry. It was seen that when the Ψ_{PD} was lower that -0.6 MPa during the green growth stage, that was a significant decrease in berry size and an inhibition of phenolic biosynthesis. This inhibition was mainly related to flavan-3-ols, proanthocyanins and anthocyanins.

However, when strong water deficits were applied in the period between véraison and maturation, biosynthesis of flavonols, anthocyanins and proanthocyanins was increased, without affecting the total flavan-3-ols biosynthesis (Ojeda *et al.,* 2002). The interaction of anthocyanin and tannin is significant and therefore water has an impact on the sensorial characteristics of the wine rather than only the final concentration of phenolic compounds. The results of Ojeda *et al.* (2002) demonstrated the impact that the skin weight and berry size had on the fruit composition and final wine quality. Anthocyanin biosynthesis may be impeded by severe water stress occurring before véraison, or conversely, may be stimulated by moderate to severe water dress after véraison (Ojeda *et al.,* 2002). The effect of water stress on the metabolism of phenols depends on the degree of water stress, but more so, on the timing and duration at which the stress is induced.

2.5.4 WINE CHEMICAL COMPOSITION

Moderate water constraints has a positive effect on the phenolic compound synthesis and grape quality, with optimum quality being obtained in seasons with low summer rain, leading to water deficit stress (Van Leeuwen *et al.,* 2004). Titratable acidity of Cabernet Sauvignon wine is predominately related to climate, especially temperature during the green berry stage. Higher temperature causes respiration of malic acid, therefore decreasing the total acid in the grape juice. Grape derived secondary metabolites are the principle sources of wine colour, aroma and flavour. Grapevine water status is reported to affect the rate of accumulation of phenolic compounds in maturing grapes. There is a clear positive effect of water deficit on berry phenolic compositions. Much research that has been done has proven that phenolic compounds of the skin play a significant role in the quality of red grapes, conferring much of the colour and structural properties to the wine (Koundouras *et al.,* 2006). Water stress could modify the value of tannin polymerisation (Ojeda *et al.,* 2002) in the grape berries influencing the wine chemical composition. Skin tissue from red grapes contain several flavanoid compound classes including anthocyanins, flavonols, flavan-3-ol monomers and proanthocyanidins. The red colour of anthocyanins that are located in the skin of the berry is extracted onto the wine. However, anthocyanins are unstable in wine and the long term colour stability in the wine results from interactions of anthocyanins and tannins to form pigmented polymers (Kennedy *et al.,* 2003; Joscelyne *et al.,* 2007). Flavonols are effective as cofactors in co-pigmentation and have health benefits. Proanthocyanidins are responsible for the bitter astringent properties of red wine (Kennedy, 2002).

2.5.5 SENSORIAL WINE QUALITY

The aromatic impacts of wines are based on perception thresholds determined in dilute alcohol solutions, wherein the true impact can be overstated as the wine matics is more complex (Pineau *et al.,* 2007). Wine sensorial quality is largely determined by the quality of the grapes from which it is made. The quality of grapes for wine depends on the variety and the environment in which the grapevines are grown (Rankine *et al.,* 1971). The significance of the viticultural environment for wine style and quality in South Africa has been recognised for a long time (Le Roux, 1974). A study was conducted by Van Leeuwen *et al.* (2004) to determine which factors had the greatest effect on growth and development of the vegetative and reproductive organs of the grapevine and the resulting wine. Of all the variables they measured, berry weight, sugar concentration and total acidity had a direct influence on the wine quality (Van Leeuwen *et al.,* 2004).

The composition of phenolics depends on the variety of grape and is influenced by environmental and viticultural factors. The final size of the berry indirectly affects the phenolic concentration of the must, as concentration depends on the skin surface to flesh ratio. The water applied is one factor that can influence berry size and which in turn, influences the nature and amount of phenolics in the grape and finally in the wine, due to the concentration effect of more skin to berry flesh (Ojeda *et al.,* 2002). Water conditions have long been recognised as an important factor determining wine grape quality, thereby affecting wine sensory attributes (Koundouras *et al.,* 2006). Grapevine water status affects fruit growth and concentration of total phenolics and wine sensory attributes and is an important tool to manipulate final wine quality in many parts of the world (Kennedy, 2002).

The overall sensory effect of ethyl propanoate, ethyl 2-methylpropanoate and ethyl 2-methylbutanoate was clearly established as the “black-berry” sensory characteristic (Pineau *et al.,* 2009). Whereas, the “red-berry” characteristics are contributed by ethyl butanoate, ethyl hexanoate, ethyl octanoate and ethyl 3-hydroxybutanoate as described by Pineau *et al*. (2009). The typical cultivar aroma of Cabernet Sauvignon can be described as being a fruity flavour of black currents and green bell peppers. A total of 48 active aroma compounds have been identified in Cabernet Sauvignon wines (Carey *et al.,* 2008). These volatile metabolites are responsible for wine varietal aroma and occur in grapes in free and glycosylated forms (Koundouras *et al.,* 2006). There is minimal information regarding the effect of either environmental parameters or grapevine water status on the volatile components of grapes and wines. Aromatic notes could be attributed to volatiles formed during fermentation from enzymatic hydrolysis of glycoconjugated precursors of the grape (Koundouras *et al.,* 2006). The total content of glycosides in wines depends on the vintage as vintage effect causes a variation in the aroma potential. Aroma and flavour compounds of wine are the less abundant secondary metabolites in the grapes. They may also be affected by the canopy light exposure. Grapevine water status has more of an indirect influence on the flavour and aroma compounds via effects on grapevine canopy.

The vegetative descriptors for Cabernet Sauvignon are bell pepper, herbaceous, tobacco, hay, artichoke, mint, freshly cut green grass and eucalyptus. These descriptors can be attributed to aldehydes and methoxypyrazines (Carey *et al.,* 2008 and references therein). The vegetative aroma resulted from the denser canopies, with excessive vegetative growth. However, higher rainfall resulted in wines with lower vegetative aroma intensity, due to the overall lower aroma intensity. The fruity descriptors in Cabernet Sauvignon are due to esters, acetate esters, fatty acids and norisoprenoids (Chapman *et al.,* 2005). When there is higher rainfall during the months before harvest wines tended to have more intense berry aroma characteristic. In seasons with normal rainfall and warmer temperatures, berry aromas were more prominent. The oxidative degradation of carotenoids present in the flesh and the skin of the grape berries give rise to a range of volatile compounds generally known as norisoprenoids (Joscelyne *et al.,* 2007). Berry aroma are associated with soils with a lower water holding capacity, due to the reduced canopy growth resulting in a more open canopy causing photo degradation of methoxypyrazines (Carey *et al.,* 2008). Fruit derived C_{13}-norisporenoid concentration increases in sun exposed grapes compared to shaded grapes. Norisoprenoids originating from carotenoid precursors in the grapes increase tends to increase after véraison (Bindon *et al.,* 2007). The increased fruity aroma significantly decreases the vegetative bell pepper aroma in wine (Marais, 1996). Pineau *et al.* (2007) also showed that β-damascenone tended to enhance fruity notes of ethyl and masked the herbaceous aroma, suggesting that β-damascenone could have a more indirect impact on the red wine aroma (Pineau *et al*., 2007). β-damascenone is one of the more frequently mentioned compounds in studies of red wine aromas, and has been established as a key odorant in red wine extracts (Pineau *et al*., 2007).

2.6 SUMMARY

The effects of climates and soil on grapevine development and grape composition can be explained by their influence on grapevine water status (Van Leeuwen *et al.,* 2004). Grapevine water status is influenced the varying amounts of summer rainfall in different vintages, while the soil influences grapevine water status through its water holding capacity. Van Leeuwen *et al.* (2004) found the best vintages for wine quality to be those in which the water balance from flowering to harvest was most negative, and the best soils to be those which induce deficits earlier in the season. Water deficits earlier in the season limited excessive vegetative growth, reducing the berry size and increasing the sugar loading as the berries are greater sinks for photosynthates. Sugar and anthocyanins have been shown to be co regulated in the grapes and thereby increasing grape quality potential (Kennedy, 2002). Wang *et al.* (2003a) concluded that the availability of water better explains the effects of berry volume, whereas the photosynthetic activity, which is related to the ratio of exposed leaf area to yield quantity accounts for the effects of phloem sugar unloading to the ripening grape berry. The kinetic monitoring of the amount of sugar per berry is a viable method of measuring the plants physiological functioning, mainly photosynthesis which is a reliable indicator of the temperature that the grapevine is subjected to and grape grapevine water status. (Hunter & Deloire, 2005; Wang *et al.,* 2003a). Climate of the season appeared to have a very strong influence on aroma characteristic of Cabernet Sauvignon wine. Warmer sites with normal seasonal rainfall can be expected to have more intense berry aroma characteristics (Carey *et al.,* 2008) and the cooler climates a more vegetative character. The biochemical evolution of berries, together with the monitoring of the water status of the grapevine, provides a more rapid determination of the vintage effect for specific cultivars on a specific terroir.

2.7 LITERATURE CITED

Améglio, T., Archer, P., Cohen, M., Valancogne, C., Daudet, F.-A., Dayau, S. and Cruiziat, P. (1999). Significance and limits in the use of predawn leaf water potential for three irrigation. *Plant and Soil*, **207**, 155-167

Amerine, M.A. & Winkler, A.J. (1944). Composition and quality of musts and wines of California grapes. *Hilgard* **15**, 493-673.

Archer, E., Swanepoel, J.J. & Strauss, H.C. (1988). Effect of plant spacing and trellising systems on grapevine root distribution. In: J.L. Van Zyl (comp.) The grapevine root and its environment, ARC Infruitec-Nietvoorbij, Private Bag X5026, 7599 Stellenbosch, South Africa. pp.74-87.

Bergqvist, J., Dokoozlian, N. & Ebisuda, N. (2001). Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in Central San Joaquin Valley of Claifornia*. Am. J. Enol. Vitic*. **52**,1-7.

Bodin, F. & Morlat, R. (2006). Characterization of viticultural terroirs using a simple field model based on soil depth I. Validation of the water supply regime, phenology and vine vigour, in the Anjou vineyard (France). *Plant and Soil*. 281, 37-54

Bonnardot, V., Carey, V., Planchon, O. & Cautenet, S. (2001). Sea breeze mechanism and observations of its effects in the Stellenbosch wine producing area. *Wineland*, October 2001, 107-113.

Bindon, K.A., Dry, P.R. & Loveys, B.R. (2007). Influence of plant water status on the production of C_{13}-norisoprenoid precursors in *Vitis vinifera* L. Cv. Cabernet Sauvignon grape berries. *J. Agric. Food Chem*. **55**, 4493-4500.

Buttrose, M., Hale, C. & Kliewer, W. (1971). Effect of temperature on the composition of Cabernet Sauvignon berries. *Am. J. Enol. Vitic.* **22**,71-75.

Carbonneau, A., Champagnol, F., Deloire, A. & Sevila, F. (1998). Harvest and grape quality. In: C. Flanzy. Oenologie. Fondements scientifiques et technologiques. pp. 647-668.

Carbonneau, A. & Deloire, A. (2001). Plant organization based on source-sink relationship: new finding on developmental, biochemical and molecular responses to environment, 263-280. In: Molecular Biology & Biotechnology of grapevine, ed. Kluwer Academic Publishers, p. 474.

Carbonneau, A., Deloire, A. & Costanza, P. (2004). Leaf water potential meaning of different modalities of measurements. *J. Int. Sci. Vigne Vin*. **38**, 15-19.

Carey, V. A., (2001). Spatial characteristic of natural terroir units for viticulture in the Bottelaryberg-Simonsberg-Helderberg winegrowinf area. Thesis, Stellenbosch University, private bag X1.

Carey, V. A., Conradie, W.J., Myburgh, P.A., Laker, M.S. & Bruwer, R.J. (2004). The significance of plant water status as a criterion in South African terroir studies. *OIV Group d'Experts: Physiologie de la vigne – 31 March 2004.*

Carey, V.A., Saayman, D., Archer, E., Barbeau, G. & Wallace, M. (2008). Viticultural terroirs in Stellenbosch, South Africa. I. The identification of natural terroirs units. *J. Int. Sci. Vigne Vin*. **42** (4), 169-183.

Chapman, D.M., Roby, G., Ebeler, S., Guinard, J-X & Matthews, M.A. (2005). Sensory attributes of Cabernet Sauvignon wines made from grapevines with different water status. *Austr. J. Grape & Wine Research* **11**, 339-347.

Choné, X., Van Leeuwen, C., Chéry, P. & Ribéreau-Gayon, P. (2001). Terroir influence on water status and nitrogen status of non-irrigated Cabernet Sauvignon (*Vitis vinifera*). Vegetative development, must and wine composition (Example of a Medoc Top Estate Vineyard, Saint Julien Area, Bordeaux, 1997). *S. Afr. J. Enol. Vitic.* **22** (1), 8-15.

Coombe, B.G. (1987). Influence of temperature on composition and quality of grapes. Acta Hort., **206**, 23-33.

Coombe, B.G. 1992. Research on development and ripening of the grape berry. *Am. J. Enol. Vitic.,* **43**, 101-110.

Coombe, B.G. & McCarthy, M.G. (2000). Dynamics of grape berry growth and physiology of ripening. Austr. Journal Grape & Wine Research. 6, 131-135.

Deloire, A., Ojeda, J., Wang, Z., Hunter, J.J., Paez, C., Martin, M. & Carbonneau, A. (2003). Grapevine water status and berry ripeness. Consequence for vineyard cultural practices. Congress of South African Society for Enology and Viticulture, 5-7 November 2003, Cape Town, South Africa.

Deloire, A., Carbonneau, A., Wang, Z. & Ojeda, H. (2004). Grapevine and water. *J. Int. Sci. Vigne Vin* **38** (1), 1-13.

Deloire, A. & Hunter, J.J. (2005). Berry composition as affected by bunch exposure. *Progres Agricole et Viticole*, **122**, 151-156.

Deloire, A., Vaudour, E., Carey, V., Bonnardot, V. & Van Leeuwen, C. (2005). Grapevine responses to terroir: A global approach. *J. Int. Sci. Vigne Vin* **39** (4), 149-162.

De Villiers, F.S., Schmidt, A., Theron, J.C.D. & Taljaard, R. (1996). Onderverdeling van die Wes-Kaapse wynbougebiede volgens bestaande klimaatskriteria. *Wynboer*, January 1996, T10-T12.

Downey, M. O., Dokoozlian, N. K., Krstic, M. P. (2006). Cultural practices and environmental impacts on the flavonoid composition of grapes and wine: A review. *Am. J. Enol. Vitic*. **57**, 257-267.

Downey, M. O., Harvey, J. S., Robinson, S. P. (2004). The effect of bunch shading on berry development and flavonoid accumulation in Shirz grapes. Aus. J. Grape & Wine Research. **10**, 55-73

Düring, H. (1976). Studies on the environmentally controlled stomatal transpiration in grapevines. I. Effects of light intensity and air humidity. *Vitis*, **15**, 82-87.

Düring, H. (1987). Stomatal responses to alterations of soil and air humidity in grapevines.*Vitis*, **26**, 9-18.

Düring, H. (1988). CO2 assimilation and photorespiration of grapevine leaves: Responses to light and drought. *Vitis*, 27, 199-208.

Düring, H. & Loveys, B.R. (1982). Diurnal changes in water relations and abscisic acid in field grown *Vitis vinifera* cvs. I.Leaf water potential components and leaf conductance under humid temperate and semiarid conditions. *Vitis,* 21, 223-232.

Fourie, J.C., Louw, P.J.E. & Agenbag, G.A. (2001). Effect of seeding date on the performance of grasses and broadleaf species evaluated for cover crop management in two wine grape regions of South Africa. *S. Afr. J. Plant Soil,* 18, 118-127.

Fregoni, M. (1977). Effects of soil and water on the quality of the harvest. In: Proc. Int. Sym. Quality of the Vintage. 14-21 February 1977, Cape Town, South Africa, 151-168.

Gladstones, J. (1992). History of climate selection for Australian viticulture. Viticulture and Environment. Winetitles, Adelaide. p. 4-7.

Greenspan, M. (2005). Integrated irrigation of California winegrapes. *Practical Vineyard & Winery*, March/April 2005, 21-43, 79.

Greenspan, M.D., Shackel, K.A. & Matthews, M.A. (1994). Developmental changes in the diurnal water budget of the grape berry exposed to water deficits. *Plant Cell Environment,* 17, 811-820.

Hillel, D. (1980). Applications of Soil Physics. Academic press, London.

Huglin, P. (1978). New method for evaluating the potential of solar thermal environments wine. In: International Symposium on Ecology of Grapevine, I, Constance, Romania, 1978. Ministry of Agriculture and Food Industry, p. 89-98.

Hunter, J.J. & Deloire, A. (2005). Relationship between sugar loading and berry size of ripening Syrah/R99 grapes as affected by grapevine water status. Gesco XIVeme journees du groupe europeen d'etude des systems de conduit de la vigne, Geisenheim, Allemagne, 23-27, 127-133.

Hunter, J.J. & Myburgh, P.A. (2001). Ecophysiological basis for water management of vineyards in South Africa, with particular reference to environmental limitations. In: Proc. GESCO Journée professionnelle: “Gestion de l’eau dans le vignoble”. Montpellier, France, 2-7 July 2001, 23-43.

Jackson, D.I. & Lombard, P.B. (1993). Environmental and management practices affecting grape composition and wine quality: A review. *Am. J. Enol. Vitic.* **44**, 409-430.

Joscelyne, V.L., Downey, M.O., Mazza, M. & Bastian, S.E. (2007). Partial shading of Cabernet Sauvigon and Shiraz vines altered wine color and mouthfeel attributes, but increased exposure had little impact. *J. Agric. Food Chem.* **55**, 10888-10896.

Kennedy, J. (2002). Understanding grape berry development. Practical Winery & Vineyard July/August 2002.

Kennedy, J. A. & Taylor, A.W. (2003). Analysis of proanthocyanidins by high-performance gel permeation chromatography. *J. Chro-matogr. A*. **995**, 99-107.

Kliewer, W., & Weaver, R. (1971). Effect of crop level and leaf area on growth, composition and coloration of Tokay grapes. *Am. J. Enol. Vitic*. **22**, 172-177.

Koundouras, S., Marinos, V., Gkoulioti, A., Kotseridis, Y. & Van Leeuwen, C. (2006). Influence of vineyard location and grapevine water status on fruit maturation of non irrigated c*v* Agiorgitiko (Vitis *vinifera* L.). Effects on wine phenolic and aroma components*. J. Agric. Food Chem*. **54**, 5077-5086.

Kramer, P.J. (1983). Water relations of plants. Academic press, New York, 489 pp.

Laker, M.S. (2004). The effect of atmospheric and soil conditions on the grapevine water status. Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Le Roux. (1974). ’n Klimaatsindeling van die Suidwes-Kaaplandse Wynbougebiede. Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Lopes, C., Vicente-Paulo, V., Santos, T., Rodrigues, M.L., Barrosso, J. & Chaves, M.M. (2001). An attempt to quantify grapevine water stress in a mediterranean environment. Montpellier, 3-7 July 2001.

Matthews, M.A., & Anderson, M.M. (1988). Fruit ripening in *Vitis vinifera* L.: Responses to seasonal water deficit. *Am. J. Enol. Vitic*. **39** (4), 313-320.

McCarthy, M.G. (1999). Is weight loss in ripening grape berries cv. Shiraz caused by impeded phloem transport? *Austr. Journal Grape & Wine Research.* 5, 17-21.

Myburgh, P.A. (1998). Water consumption of South African vineyards: A modeling approach based on the quantified combined effects of selected viticultural, soil and meteorological parameters. Dissweration, University of Stellenbosch, Private Bag X1, Matieland, 7602, South Africa.

Myburgh, P.A. (2003a). Possible flood irrigation technologies to reduce water use of Sultanina grapevines in a hot, arid climate. *S. Afr. J. Plant Soil* **20**, 180-186.

Myburgh, P.A. (2003b). Responses of Vitis vinifera L*. cv.* Sultanina to level of soil water depletion under semi-arid conditions. *S. Afr. J. Enol. Vitic.* **24**, 16-24.

Myburgh, P.A. (2005a). Water status, vegetative growth and yield responses of *Vitis vinifera* L. *cvs.* Sauvignon blanc and Chenin blanc to timing of irrigation during berry ripening in the Coastal Region of South Africa. *S. Afr. J. Enol. Vitic*. **26**, 59-67.

Myburgh, P.A. (2005b). Effect of altitude and distance from the Atlantic Ocean on mean February temperatures in the Western Cape Coastal Region. *Wynboer Technical Yearbook*, 49-52.

Ojeda, H., Andary, C., Kraeva, E., Carbonneau, A. & Deloire, A. (2002). Influence of pre- and post véraison water deficits on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. *Am. J. Enol. Vitic.* **53**, 261-267.

Ojeda, H., Deloire, A. & Carbonneau, A. (2001). Influence of water deficits on grape berry growth. *Vitis* **49**, 141-145.

Olivo, N., Girona, J. & Marsal, J. (2009) Seasonal sensitivity of stem water potential to vapour pressure deficit in grapevine. *Irrig Sci.* **27**, 175-182.

Pineau, B., Barbe, J.-C., Van Leeuwen, C. and Dubourdieu, D. (2007). Which impact for B-Damascanone on red wine aroma? *J. Agric. Food Chem*., **55**, 4103-4108.

Pineau, B., Barbe, J.-C., Van Leeuwen, C. and Dubourdieu, D. (2009). Examples of perceptive interactions involved in specific "red-" and "black-berry" aromas in red wines. *J. Agric. Food Chem.,* 57, 3702-3708.Rankine, B.C., Fornachon, J.C.M., Boehm, E.W. & Cellier, K.M. (1971). Influence of grape variety, climate and soil on grape composition and on the composition and quality of table wines. *Vitis* **10**, 33-50.

Saayman, D. (1992). Natural influences and wine quality. Part 2: The role of soil. *Wynboer*, August 1992, 49-51.

Scholander, P.F., Hammel, H.J., Bradstreet, A. & Hemmingsen, E.A. (1965). Sap pressure in vascular plants. *Science* **148**, 339-346.

Schultz H.R., Matthews, M.A. (1993). Xylem development and hydraulic conductance in sun and shade shoots of grapevine (Vitis vinifera L.), evidence that low light uncouples water transport capacity from leaf area. *Planta* **190**, 393-406.

Smart, R. (1985). Principles of grapevine canopy microclimate manipulations with implications for yield and quality. A review*, Am.J. Enol. Vitic*. **36,** 230-239.

Smart, R.E. & Coombe, B.G. (1983). Water relations of grapevines. In: Kozlowski T.T. (Ed). Water deficits and plant growth VII. Academic press, New York. 137-796.

Smart, R.E. & Dry, P.R. (1980). A climatic classification for Australian viticultural regions. *Austr. Grapegrower & Winemaker* **196**, 9-16.

Spayd, S., J. Tarara, D. Mee, and J. Ferguson.(2002). Seperation of sunlight and temperature effects on the composition of *Vitis vinifera cv.* Merlot berries*. Am. J. Enol. Vitic.* **53**:171-182.

Tonietto, J. & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agric. Forest Meteorology.* **124**, 81-97.

Tonietto, J.(1999). Les macroclimates viticole mondiaux et l'influence du mésoclimat sur la typieite de la Syrah et du Muscate de Hambourg dans le sud de la France. Methologie de caracteristion. *PhD Thése, Ecole Nationale Supérieure Agronomique de Montpellier.*

Van Huyssteen, L., Van Zyl, J.L. & Koen, A.P. (1984). The effect of cover crop managment on soil conditions and weed control in a Colombar vineyard in Oudshoorn, *S. Afr. J. Enol. Vitic.* **5,** 7-17.

Van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S. & Dubourdieu, D. (2004). Influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic*. **55** , 207-217.

Van Leeuwen, C. & Seguin, G. (1994).Incidences de l'alimentation en eau da la vigne, appréciéé par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (*Vitis vinifera* variété Cabernet franc, Saint-Emilion, 1990). *J. Int. Sci. Vigne Vin*. 28, 81-110.

Van Zyl, J.L. (1975). Wingerdbesproeing in die Stellenbosch-gebied binne die raamwerk van die plaaslke grond-water-plant-atmosfeer-kontinuum. Thesis, Stellenbosch University, Private bag X1, 7602 Matieland (Stellenbosch), South Africa.

Van Zyl, J.L. (1981). Waterbehoefte en besproeiing. In: Burger, J. & Deist, J. (eds.) Wingerdbou in Suid-Afrika. CTP Boekdrukkers, Cape Town, p. 237-238.

Van Zyl, J.L. (1986). Canopy temperature as a water stress indicator in grapevines. *S. Afr. J. Enol. Vitic.* **7**, 2.

Van Zyl, J.L. (1987). Diurnal variation in grapevine water stress as a function of changing soil water status and meteorological conditions. *S. Afr. J. Enol. Vitic.* **8**, 45-52.

Van Zyl, J.L & Van Huyssteen, L. (1979). Die indeling van gronde volgens potensiaal vir wyndruiwe met spesiale verwysing na die Bo-Bergriviervallei. Wynboer 573, 46-27, 57-58, 60.

Van Zyl, J.L & Van Huyssteen, L. (1984). Soil and water management for optimum grape yield and quality under conditions limited or no irrigation. In: Proc. 5th Australian Wine Industry Technical Conf., November-December 1983, University of Western Australia, Perth, Australia. pp 25-66.

Van Zyl, J.L. & Weber, H.W. (1981). The effect of various supplementary irrigation treatments on plant and soil moisture relationships in a vineyard. *S. Afr. J. Enol. Vitic.* **2**, 83-99.

Wang, Z.P., Deloire, A., Carbonneau, A., Federspiel, B. & Lopez, F. (2003a). An in vivo experimental system to study sugar phloem unloading in ripening grape berries during water deficiency stress. *Annals of Botany* **92**, 523-528.

Wang, Z.P., Deloire, A., Carbonneau, A., Federspiel, B. & Lopez, F. (2003b). Study of sugar phloem unloading in ripening grape berries under water stress conditions*. J. Int. Sci. Vignee et Vin,* **37**, 213-222.

Winkel, T. & Rambal, S. (1990). Stomatal conductance of some grapevines growing in the field under a Mediterranean environment. *Agric. For. Meteorol.,* **51**, 107.

Winkel, T. & Rambal, S. (1993). Influence of water stress on grapevines growing in the field: From leave to whole-plant response. *Austr. J. Plant Physiol*. **20**, 143-157.

Williams, L.E. & Araujo, F.J. (2002). Correlations among predawn leaf, midday leaf and midday stem water potential and their correlations with other measures of soil and plant water status in *Vitis vinifera. J. Amer. Soc. Hort. Sci.* **127** , 448-454.

Williams, L.E., Dokoozlian, N.K. & Wample, R. (1994). Grape. In: Shaffer, B & Anderson, P.C. (Eds). Handbook of environmental physiology of fruit crops, Vol I, Temperate crops. CRC Press, Boca Raton, 85-133.

Chapter 3

RESEARCH RESULTS

DESCRIPTION OF CLIMATE, SOIL CONDITIONS AND ROOT STRUCTURES IN CABERNET SAUVIGNON VINEYARDS (*Vitis Vinifera* L.) AT TWO LOCALITIES IN THE SWARTLAND REGION

DESCRIPTION OF CLIMATE, SOIL CONDITIONS AND ROOT STRUCTURES IN CABERNET SAUVIGNON VINEYARDS (*VITIS VINIFERA* L.) AT TWO LOCALITIES IN THE SWARTLAND REGION.

3.1 INTRODUCTION

In viticulture, climate is described at three levels, namely macro climate on a regional scale, meso climate on a site scale and micro climate in the canopy (Smart, 1985). Macro climate can be defined as the climate of a region and describes the temperature variation on a small scale. Meso climate is more site specific due to differences in altitude, slope inclination, aspect and distance from large bodies of water and describes the climate of the specific vineyard. Recent studies have emphasized the important effects of meso climate especially for marginal growing conditions (Smart, 1985). Canopy microclimate depends on the amount and distribution of leaf area and its interaction with the above ground climate.

Climate, in particular temperature plays an important role in determining wine style and quality (Le Roux, 1974; De Villiers *et al*., 1996). Temperature is probably one of the most important parameters affecting grapevine growth, and has an effect on almost every aspect of the grapevine physiological functioning. Phenological development and growth of the grapevine is temperature driven. Every facet of plant growth and development, each physical process, enzymatic reaction, membrane field, transport processes and phase transition is separately subjected to the influence of temperature (Coombe, 1987 and references therein). High temperatures reduce anthocyanin accumulation and the optimum temperature range for anthocyanin synthesis is between 30˚C and 35˚C (Spayd *et al*., 2002). Temperature has also been acknowledged to have a major influence on the grape composition and quality (Coombe, 1987). Furthermore, air temperature is one of the most important atmospheric variables for viticulture (Myburgh, 2005a) as it plays an important role in grapevine development and ultimately influencing juice and final wine quality and aroma (Carey *et al.,* 2001).

Relative humidity and temperature determines the saturation deficit of the air. This saturation deficit contributes to water stress and is more prominent when the temperature is higher. High saturation deficit, as a result of low relative humidity and high temperature, results in high berry pH values and reduced growth and yield. Sunlight stimulates berry anthocyanin accumulation (Smart, 1985; Spayd *et al.,* 2002). The intensity of solar radiation has a direct effect on the production of phenolic compounds and this can have a significant influence on the grapevine resistance to downy mildew (Dalla Marta *et al.,* 2008). Wind can have a positive or negative effect on grapevine growth. Strong winds in spring and early summer can have a negative influence because the new growth on the grapevine in injured and fruit set is reduced. Wind speed of 3 to 4 m/s can result in the closure of the stomata, thereby causing an inhibition of photosynthesis. Sea breezes can be defined as a local wind occurring during the afternoon due to the differential heating above the land and the sea (Bonnardot *et al.,* 2001). Cooling sea breezes in the afternoon can have a positive effect on photosynthesis and air circulation in the canopy. This prevents high relative humidity and high temperatures in the grapevine canopy. Coastal sites have the benefit of dry land winds at night and cool afternoon ocean breezes. The sea breezes reduce the saturation deficit, lower maximum temperature and there is a slower decrease in evening temperature, resulting in a longer period for photosynthesis and physiological ripening.

Carey (2001) notes that some climate classifications are for global viticulture application, such as the ones proposed by Smart & Dry (1980), Huglin (1978), Gladstones (1992) and Tonietto (1999). Adaptations have made some classifications applicable to specific countries such as South Africa (Le Roux, 1974; De Villiers *et al.,* 1996) or regions (Amerine & Winkler, 1944). Long term weather data, e.g. mean February temperature (MFT), is used as a criterion to determine wine quality potential of a specific region (De Villiers *et al.,* 1996; Myburgh, 2005b). De Villiers *et al*. (1996) divided the South Western Cape into different climatic regions according to MFT. February is the warmest month in many parts of the Western Cape and it is the month during which the majority of the grapes ripen. Mean February temperature is based on the concept of Smart & Dry (1980) and was adapted by De Villiers *et al.* (1996). The primary classes are as follows:

MFT (˚C)	Climatic class	Wine Potential
17-18.9	Cold	High quality white table wine
19-20.9	Cool	High quality white and red table wines
21-22.9	Moderate	High quality red table wines
23-24.9	Hot	Low acid, high pH
>25	Very hot	Low acid, high pH

One of the most well known temperature indices for viticulture is that of the growing degree days (GDD), as first suggested by Amerine & Winkler (1944) for California (hereafter referred to as the Winkler index). The heat summation technique was applied to the Western Cape wine producing regions and adapted the growing season and classification was adapted to make it relevant for South African conditions (Le Roux, 1974). The growing season is from 1st September to 30th March and is calculated as a summation of the daily mean temperature above 10˚C. The adapted climatic criteria for the Western Cape regions are as follows:

Degree days (˚C)	Region	Viticulture potential
<1389	I	Quality red and white wine
1389-1666	II	Good quality red and white table wine
1667-1943	III	Red and white table wine and port
1944-2220	IV	Dessert wine, sherry and standard quality table wine
>2200	V	Dessert wine and brandy

The heliothermal index (HI) is used worldwide to describe the potential for viticulture (Huglin, 1978). This index is based on the mean and maximum monthly temperatures from October to March (Huglin, 1978; Tonietto & Carbonneau, 2004). The calculation incorporates a coefficient to allow for the greatest photosynthetic active radiation that occurs with longer days at higher altitudes. A coefficient of one is used for the Southern Western Cape (latitude 34˚ South). This index provides information regarding the level of heliothermal potential. It provides a better indication of the sugar loading potential according to the varieties rather than the classic temperature summations, thereby providing qualitative information (Tonietto & Carbonneau, 2004). The HI intervals and classes are as follows:

Huglin Index	Climate	Viticultural potential
IH1: 1400-1500	Very cool	Only very early cultivars can ripen
IH2: 1500-1800	Cool	A large scale of cultivars can ripen
IH3: 1800-2100	Temperate	Late cultivars can reach maturity
IH4: 2100-2400	Warm temperate	No further heliothermic constraints for ripening
IH5: 2400-3000	Hot	Exceeds heliothermic requirements, high temperature stress
IH6: >3000	Very hot	Possibility of two harvest per year, high temperature stress

A good discrimination of the region’s climate with regard to global heliothermal conditions during the vegetative cycle of grapevines and cool night conditions during the ripening period can be obtained when HI is used in conjunction with cool night index (CI) (Tonietto & Carbonneau, 2004). The CI is the night coolness variable and is quantified using the mean minimum night temperature during the month preceding harvest (Tonietto & Carbonneau, 2004). This index is used to determine the qualitative potential of wine growing regions with respect to wine colour and aroma, notably in relation to secondary metabolites (polyphenols and aromas) in grapes. The index is based on the minimum temperature during the month of March, i.e. the period when many of the red cultivars ripen. The CI classes and intervals are as follows:

Mean minimum March temperature (˚C)	Climate	Cultivation potential
IF1: >18	Warm night	High night temperature throughout maturation period
IF2: 14-18	Temperate nights	Late cultivars ripen under cooler night temperatures
IF3: 12-14	Cool nights	Ripening under cooler night temperatures
IF4: <12	Very cool nights	Critical night temperature

Terroir is defined as a complex of natural environmental factors (topography, climate, soil and parent material), resulting in distinctive wines with identifiable origins expressed in the final product (Carey *et al.,* 2001). According to Van Leeuwen *et al*. (2004), the three parameters of terroir are soil, cultivar and climate (through the vintage effect), having a highly significant effect on the grapevine development and berry composition. The significance of the viticultural environment for wine style and wine quality in South Africa has long been recognized (Le Roux, 1974; Saayman, 1977; Carey *et al.,* 2008). Environmental parameters such as climate (rainfall, relative humidity, air temperature, soil temperature, direction and intensity of dominant winds), topography (slope, exposition, sunlight exposure and landscape form) and soil (mineralogy, compaction, texture, soil water reserve, depth, and colour) have an overriding effect on the performance of Cabernet Sauvignon grapevines (Carey *et al.,* 2008 and references therein). In addition vintage, soil and topographic related site characteristics and scion clone can affect the phenology, growth, yield, berry composition and wine related parameters of Cabernet Sauvignon grapevines (Carey *et al.*, 2008).

The effect of climate and soil on grapevine development and grape composition can, to a large extent, be reasoned using the influence on the grapevine water status (Van Leeuwen *et al*., 2004). The soil water holding capacity, and therefore plant available water, is determined by the soil characteristics and the root distribution of the grapevine (Van Zyl, 1981). The intensity of grapevine water stress depends not only on climatic parameters but also on the water holding capacity of the soil (Van Leeuwen *et al.,* 2004). Many studies indicate the positive impact of moderate water deficits on phenolic compound synthesis and grape quality (Van Leeuwen *et al.,* 2004; Ojeda *et al.,* 2002). Soil with low water holding capacity produced wines that were inclined to be fruity, in contrast to more vegetative wines produced where soils had a higher water holding capacity (Chapman *et al.,* 2005). Water holding capacity is to a large extent determined by soil texture. Carey *et al.* (2008) related the capacity of the grapevines to soil texture. Water deficit early in the season leads to early shoot cessation and reduced berry size, whilst the berry sugar and anthocyanin concentration are increased because of the greater ripening tempo (Van Leeuwen *et al.*, 2004). Irrigation can have positive or detrimental effects on growth, yield and wine quality (Tesic *et al.*, 2002; Acevedo *et al.,* 2004; Chapman *et al.,* 2005; Santalucia *et al.,* 2007). This could be as a result of direct or indirect effects on the grapevine physiological and morphological processes. Vineyards with the potential to produce wine of high quality are usually located in climatic regions and/or in soils resulting in water supply to the plant being lower than potential evapotranspiration (Pellegrino *et al.,* 2004 and references therein).

The aims of this study was (i) to analyse the climate, (ii) to determine if different terroirs could be identified and (iii) to determine the effect of climate and irrigation on soil water status in Cabernet Sauvignon vineyards at two localities in the Swartland region of the Western Cape.

3.2 MATERIALS AND METHODS

3.2.1 EXPERIMENT LAYOUT

The experiment was carried out during the 2007/08 and 2008/09 growing seasons in the Swartland grape growing region of the Western Cape province. Within this region, two commercially grown Cabernet Sauvignon vineyards in a warm and cool climate were selected in collaboration with experienced viticulturalists who are familiar with the vineyards in this particular region. The main plots were near Philadelphia and Wellington, respectively, in comparable soil types. The two localities were respectively 12 km (Philadelphia) and 51 km (Wellington) from the ocean (Fig. 3.1). Hereinafter, the sites near Wellington and Philadelphia are referred to as Wellington and Philadelphia. The planting date, plant material, plant spacing and trellis system are presented in Table 3.1. Each main plot was further divided into three plots (Table 3.2). In the first plot, grapevines were cultivated not irrigated (*i.e.* non-irrigated or rain fed), whereas the second plot was irrigated using a single dripper line in the grapevine rows. The third plot was irrigated with two dripper lines, one in the vine rows and the other in the middle of the work rows. Irrigation was applied according to the grower's normal irrigation schedule. Irrigation volumes were recorded using water meters and were monitored at least once a month. The amount of irrigation water applied to grapevines at Wellington was approximately four times more than the water applied at the locality near Philadelphia. The amount of water applied in 2007/08 and 2008/09 at Wellington was similar, whereas at Philadelphia almost double the amount of water was applied in the 2008/09 season compared to the 2007/08 season (Table 3.3).

Each experiment plot consisted of two experiment rows of six grapevines each (Fig. 3.2). There were two buffer grapevines at the end of each experiment row and a buffer row on each side to reduce overlapping treatment effects. The grapevines were spur pruned annually, to an average of 20 buds per meter cordon. Suckering, *i.e.* the removal of shoots that are not growing from the selected fruiting canes was carried out when the shoots were about 15 cm long. Limited shoot positioning was carried out in November.

3.2.2 CLIMATE

The climate in the region was described using long term air temperature, relative humidity (RH), rainfall, wind speed and incoming solar radiation (insolation). This weather data was obtained from the ARC Institute for Soil Climate and Water in Pretoria (Table 3.4). The prevailing weather conditions during the study period, *i.e.* September 2007 until March 2008 (season one) and September 2008 until March 2009 (season two), was recorded by means of two automatic weather stations (MC Systems, Cape Town) installed near the plots at Philadelphia and Wellington, respectively. The automatic weather stations recorded the temperature, rainfall, net radiation, hours of sunshine and wind speed. Hourly data sets ware used to calculate the daily maximum and minimum temperature and the mean temperatures. This data was used to classify the site according to the Winkler and Huglin indices (Conradie *et al.,* 2002). The long term data was used to classify the climate of the area on a macro climatic scale and to compare the prevailing atmospheric conditions during the

2007/08 and the 2008/09 season to the long term mean for the study area. The Winkler index was calculated for both climatic sites using the mean data from the weather stations.

Temperature in the bunch zone was measured every 15 minutes by means of electronic sensors and recorded using data loggers (Tinytag, Gemini, Rondebosch Cape Town). These data were used to calculate Winkler, Huglin, MFT and the CI indices for each site classifying each at the grapevine canopy level.

3.2.3 QUANTIFICATION OF SOIL CONDITIONS

3.2.3.1 Soil classification and analyses

The soils were classified and described at form and family level according to the South African Soil Classification System (Soil Classification Working Group, 1991). Soil samples were collected over 300 mm increments to a depth of 900 mm in the soil pits. Soil pH, electrical conductivity of the saturated soil extract (EC_e), phosphorus, potassium, exchangeable cations (sodium, potassium, calcium & magnesium), micro nutrients (copper, zinc, manganese & boron) and organic carbon contents were determined. Physical properties, *i.e.* soil particle size distribution and plant available water (PAW), were also determined. All analyses were carried out by a commercial laboratory (BEMLAB, Strand) according to their standard methods.

3.2.3.2. Measurement of soil water status

The soil water status was measured at 300 mm, 600 mm and 900 mm depths by means of the neutron scattering technique. Two neutron probe access tubes were installed in each of the grapevine rows about 500 mm from a grapevine trunk in each plot. Soil water status was measured twice a week from bud break when the soil was drying out at a rapid rate. Once the drying had tapered off, the water status was measured once a week throughout the season till two weeks post harvest. The soil water matric potential (Ψ_M) was measured by means of Bourdon gauge type tensiometers at 300 mm, 600 mm and 900 mm depths at the same frequency as the neutron probe measurements. At each locality, two sets of tensiometers were installed approximately 400 mm from the neutron probe access tubes in the single drip line plots. The neutron probe (HYDROPROBE 305DR, CPN, California) was calibrated against Ψ_M. The relationship between neutron probe count ratio and Ψ_M was determined for each depth. These “soil water characteristic curves” were used to convert neutron probe count ratios to Ψ_M. The equations developed to convert neutron probe count ratio to Ψ_M are presented in Table 3.5. Examples of soil water characteristic curves representing the different soil layers are presented in Figure 3.3 and 3.4.

3.2.3.3. Estimation of evapotranspiration

Daily evapotranspiration (ET) of the vineyards at the two localities was estimated using crop coefficients (K_c) determined for non-irrigated vineyards near Stellenbosch (Laker, 2004) and a reference evapotranspiration (ET_o). The long term mean daily American Class-A pan evaporation measured at Philadelphia and Wellington (Anonymous, 1989) was multiplied with a conversion factor of 0.6 to obtain ET_o. Estimated monthly ET values were summed to obtain the total over the growing period, *i.e.* from September until March. A simple "water balance" was calculated for the non-irrigated grapevines at each locality by subtracting ET from the sum of the PAW and rainfall for each of the two seasons. Only rainfall events in excess of 10 mm were considered to be effective.

3.2.4 ROOT STUDIES

The root structures of the experiment grapevines were determined in October 2009 once the soil had dried out after the winter rain. The objective of the root studies was to quantify the reaction of the roots to the soil type. Therefore, roots studies were only carried out where grapevines were irrigated by means of a single drip line. The profile wall method of Böhm (1979) was used to quantify and qualify the root distribution within the constraints of the method. A trench was dug across the grapevine row between two experiment grapevines. Each side of the trench was approximately 150 mm from the grapevine trunks. The trench was 1 m deep and 3 m wide to obtain a representative area for the mapping of the roots. A portable steel grid, divided into 100 mm squares was placed over the root profile and the exposed roots were counted and mapped in every block. The roots were classified into four classes, *i.e.* fine (<0.5 mm diameter), medium (0.5 mm to 2.0 mm diameter), coarse (2.0 mm to 5.0 mm diameter) and thick (> 5.0 mm diameter). The exposed roots were painted white using PVA paint so that they would be more visible on photographs.

3.3 RESULTS AND DISCUSSION

3.3.1 CLIMATE

3.3.1.1 Long term weather conditions and prevailing atmospheric conditions

Climatic indices: In a large wine producing region such as the Swartland, fluctuations in temperature due to variation in altitude and topography can be expected (Carey *et al.,* 2008). This could be explained by the diminishing of the cooling effect of the sea breeze as the distance to the Atlantic Ocean increases from 12 km (Philadelphia) to 51 km (Wellington). It has been shown that the proximity of the Atlantic Ocean and altitude have a significant effect on the MFT in the Western Cape Coastal Region and the sea breeze effect can occur as far a 60 km inland (Myburgh, 2005b). According to the MFT index (De Villiers *et al.,* 1996), Philadelphia can be classified as moderate, whereas Wellington is hot to very hot (Table 3.6). Based on MFT, vineyards near Philadelphia have the potential to produce high quality red wine with high acid and low pH. On the other hand, vineyards near Wellington have the potential to produce wines with low acidity and high pH.

Using the HI (Huglin, 1978), the Swartland region can also be divided into two climatic regions. However, there was no difference in the CI (Toneitto & Carbonneau, 2004) between the two localities (Table 3.6). The lack of difference could be due to the fact that the vineyard near Wellington was situated on a hill, causing the heavier cool air to sink and warm air to rise during the night (Carey, 2005). Therefore, the accumulative cooling units decreased as the cool air moved downhill. Furthermore, there was also a dam approximately 200 m from the vineyard which could have had a moderating influence on the night temperature (Carey, 2005). As expected, the night temperature at the site near Philadelphia was moderate due to the close proximity to the Atlantic Ocean and the vineyard being situated mid slope (Table 3.6).

During the 2007/08 and 2008/09 seasons, the GDD near Wellington was slightly lower than the long term mean of 2421 (Table 3.6). Since, the GDD values were within the Winkler class V, the locality can be classified as warm to hot. During the 2007/08 and 2008/09 seasons, the GDD near Philadelphia was in the Winkler class III, which indicated that this locality had moderate temperatures suitable for producing red and white wine as well as port (Table 3.6). However, according to the long term mean of 1983 GDD Philadelphia should be classified as a class IV region rather than a class III region. The heat summation of the locality near Philadelphia could have been influenced by the position of the old weather station which is not in operation any more. Since the old weather station was situated in a topographic depression, it could have adjusted the long term mean towards warmer conditions compared to the more exposed new weather station situated mid slope on a hill. The new weather station was calibrated correctly. Therefore, the change in position could not have changed the long term trend. As the area is not cool, the weather station did not mask any effects, therefore the weather data is still relevant in classifying the area as moderate. At both localities, the seasonal GDD was slightly cooler than the long term mean, therefore explaining the typical vintage effect common to South Africa (A. Deloire, personal communication). As Philadelphia is a moderate temperature region, and the cool moderate temperatures could vary due to wind and ocean breezes, there could be a shift towards the warmer Winkler classes. However, for Wellington which is already hot, a shift of classes is unlikely to occur. The vintage effect is more prominent in regions with cool moderate climates. According to the heliothermal index, Wellington and Philadelphia could also be classified into two classes, *i.e*. IH5 and IH4, respectively (Table 3.6).

Maximum temperature: The highest mean maximum temperature for both localities occurred in February, with the highest temperature 31.8˚C and 27.9˚C for Wellington and Philadelphia, respectively (Table 3.4). Wellington which is approximately 50 km inland from the coast was *ca.* 4˚C warmer than Philadelphia. The sea breeze effect from False Bay, penetrating about 100 km inland, had a significant effect on mean maximum temperatures in the Stellenbosch wine producing area, and the mean temperature at weather stations located approximately 50 km from the coast increased by about 4˚C (Bonnardot *et al.,* 2001). The difference between Philadelphia and Wellington clearly reflected the effect of proximity to the Ocean. The maximum temperature at Wellington falls outside the optimal range for photosynthesis, which is between 20˚C to 30˚C. The lowest net photosynthesis rate have been recorded at 35˚C, and this can be attributed to biochemical factors of an enzymatic nature rather than stomata functioning (Ferrini *et al.,*1995). The optimum temperature range for anthocyanin synthesis is between 30˚C and 35˚C (Spayd *et al.,* 2002). Degradation of physiological grapevine functioning occurs when temperatures are either below 15˚C or above 35˚C.

The maximum monthly temperature over the growing season showed similar trends during the two seasons (Fig. 3.5). However, at Wellington seasonal temperatures tended to be just below the long term mean trend for the beginning of the season, and close to long term mean trend for the rest of the season (Fig. 3.5A). Philadelphia showed no considerable seasonal differences and the monthly maximum temperatures in the 2008/09 season were comparable to the 2007/08 season and the long term means (Fig. 3.5B). The seasonal mean maximum temperatures at both localities were similar to the long term mean and showing no differences between the 2007/08 and 2008/09 seasons (Fig. 3.6).

Lower maximum temperatures were measured in grapevine canopies at Philadelphia in comparison to the ones at Wellington (Fig 3.7). No significant seasonal differences occurred at both localities, except that the 2007/08 season had higher mean March maximum temperatures in the canopies at both localities. The seasonal canopy temperature near Wellington was higher than the mean long term whereas temperatures within the canopy at Philadelphia were closer to the mean long term (Fig. 3.7B). Temperature also decreased with increasing canopy density (data not shown). The higher canopy temperatures in February during the two seasons at Wellington could have a potential negative effect on the grapevine functioning. Since February is the month when most of the ripening takes place in Cabernet Sauvignon vineyards, the demand for metabolites by the sink is higher and an increase in temperature could limit photosynthesis at the source (Ferrini *et al.,* 1995).

Minimum temperature: The minimum monthly temperature throughout the season for Wellington was similar during both seasons, with the minimum temperatures being comparable to the long term mean (Fig. 3.5A). At Philadelphia, the minimum temperatures during 2007/08 were also similar to the long term mean (Fig. 3.5B). However, minimum temperatures in 2008/09 were lower than both the long term mean and the temperatures recorded in 2007/08. Although the seasonal mean minimum temperature at both localities were slightly less than the long term mean, there were no differences between the 2007/08 and 2008/09 seasons (Fig. 3.6). It was previously shown that more fluctuations in temperature occur in the coastal wine growing regions compared to further inland due to the sea breeze mechanism (Planchon *et al.,* 2000). At Wellington, the night temperature was moderated by the topography of the vineyard and the dam close by, whereas the sea breezes had a moderating effect at Philadelphia as discussed above. With the exception of higher minimum canopy temperature during March in the 2008/09 season, there was no difference between the two seasons and the long term means (Fig 3.6).

Ripening hours: The total hours between the optimal grapevine functioning range of 15˚C to 35˚C, showed that the favourable ripening hours tended to increase closer to the ocean (Fig. 3.8A). The hours where the temperature was above 35˚C, *i.e.* where grapevine functioning is impeded (A. Deloire, personal communication), showed that the grapevines at Wellington experienced more hours above this critical temperature threshold (Fig 3.8B). However, hours more than 35˚C probably did not occur to such an extent that it would have had a negative effect on the grapevine functioning, proving that temperature has less of a driving effect in comparison to grapevine water constraints induced by soil water deficits.

Relative humidity: The sea breeze penetrates up to approximately 100 km inland and causes the relative humidity (RH) to decrease rapidly with an increase in distance from the coast (Bonnardot *et al.,* 2001). As expected, the RH at Wellington was lower compared to Philadelphia (Table 3.4). The maximum RH at Wellington was lower than the long term mean during both seasons (Fig. 3.9A). During 2007/08, the minimum RH at Wellington was higher than the long term mean, but for 2008/09 it was comparable to the long term mean. The maximum and minimum RH at Philadelphia for both seasons was comparable to the long term mean (Fig 3.9B). This could be explained by the proximity to the ocean, and the constant air movement due to the wind blowing from the coast.

Insolation: Solar radiation plays an important role on meteorological elements such as temperature and rain (Dalla Marta *et al.,* 2008). Insolation was higher at Wellington than at Philadelphia (Table 3.4). During the 2007/08 and 2008/09 seasons, mean daily insolation at Wellington was almost identical to the long term mean and there was also no seasonal variation (Fig. 3.10A). At Philadelphia the seasonal insolation fluctuated around the long term mean and followed a similar trend to that at Wellington (Fig 3.10B). The solar radiation did not vary significantly between the two localities irrespective of the climatic differences between them.

Wind speed: At both localities, the strongest mean daily wind speeds occurred during November, December and January (Table 3.4). Wind speed above 2 m/s starts to remove accumulated heat units and has a cooling effect on the grapevine (Williams *et al.,* 1994, references therein). Since the wind speed was above 2 m/s throughout both seasons, a substantial amount of accumulated heat units could have been lost. This could have positive effects on grapevine physiology in a warmer region and negative effects in a cooler region. Wind also increases vineyard evapotranspiration due to air circulation which increases transpiration. However, wind speed above 4 m/s will induce stomatal closure in the grapevine leaves (Greenspan, 2008), and will reduce the grapevine transpiration (Campbell-Clause, 1998). This suggested that the high wind speeds that occurred at Philadelphia from November to February (Table 3.4) could have reduced transpiration and grapevine functioning. The average wind speed at Wellington was higher throughout the season compared to the long term mean (Fig. 3.11A). In 2008/09, the wind speed at Philadelphia was also higher than the long term mean for most of the season (Fig. 3.11B). In 2007/08, wind speed did not show any particular trend with respect to the long term mean. The higher average wind speed at Philadelphia was probably caused by closer proximity to the ocean compared to Wellington.

Rainfall: The Swartland region receives most of its annual rainfall between May and August and the region is classified as a Mediterranean rainfall region (Fig. 3.12A & Fig. 3.12B). However, the monthly rainfall for each season was not comparable and differed substantially from the long term means. At Wellington and Philadelphia total annual rainfall was comparable to the long term mean (Fig 3.12C). Since unexpected rain can influence the plant water status and cause vintage effects (Van Leeuwen *et al.,* 2004), highly variable rainfall in the Swartland grape growing region could induce different grapevine responses between seasons.

3.3.2 SOIL CONDITIONS

3.3.2.1 Physical properties

The soil near Wellington contained a low percentage stones, whereas no stones were present in the soil at Philadelphia (Table 3.7). The topsoil at Philadelphia contained slightly more clay than the topsoil at Wellington. However, the subsoil at Wellington contained slightly more clay than at Philadelphia. The silt percentage was about 6% higher near Wellington in comparison to Philadelphia. The fine sand in the soil at Philadelphia was 10-20% more than at Wellington. The fine sand fraction in the soils tended to increase and the coarse sand decreased as the distance to the Atlantic Ocean decreased. Both soils had a sandy loam texture, with the exception of the sandy clay loam subsoil at Philadelphia (Table 3.7). Since the soil texture was comparable at the two localities, the plant available water (PAW) was comparable between at Wellington and Philadelphia. The absence of differences between the soil water holding capacity eliminates the effect of this important variable from the study. Soil type influences the vintage effect, since the soil influences the grapevine water status through its water holding capacity and the presence of a water table (Van Leeuwen *et al*., 2004).

3.3.2.2 Chemical properties

The topsoil pH_{KCl} was close to 6.0, therefore no severe acidity problems occurred in either one of the soils at the two localities (Table 3.8). When the pH_{KCl} is less than 5.5, the soil is classified as acidic and phosphates become unavailable due to precipitation with free anions (Bates *et al.,* 2002). When the soil pH_{KCl} is greater than 8.0, the soil is classified as alkaline. The Western Cape is known to have slightly acidic subsoils. Although the subsoil at both localities was near the lower limit for the soil to be regarded as acidic, it was probably not low enough to cause severe negative effects on grapevine growth. Furthermore, no salinity problems occurred in any of the soils. There were no dominating salts in the soil. Hence, there appeared to be no problem regarding the soil chemistry in both soils. The nutrient level in the soil showed that the grapevines were not subjected to any nutrient deficiencies or toxicities. The soil chemistry of both soils was similar and can be eliminated as a variable that could have caused variation in grapevine growth between the two localities. No direct relationship can be established between soil minerals, with the exception of nitrogen and wine quality, as long as severe deficiencies do not interact with normal plant functioning (Van Leeuwen *et al*., 2004).

3.3.3 SOIL WATER STATUS

Soil matric potential (Ψ_M) is the energy which roots must exert to absorb water from the soil. When the soil is wet, roots do not need to exert a great deal of energy and water is taken up very easily, whereas increasingly more energy is required to absorb water as the soil dries out. Previous studies have shown that the onset of water constraints in grapevines begins when Ψ_M reaches -0.064 MPa (Van Zyl, 1987). Recent studies have shown that water constraints could be induced at a Ψ_M value of about -0.10 MPa in some sandy and gravelly soils (P.A. Myburgh, personal communication).

At Wellington, the seasonal Ψ_M showed little differences between the 2007/08 and 2008/09 seasons (Figs. 3.13). In the non-irrigated plot, the threshold for the onset of water constraints occurred in November during both seasons. In the 2007/08 season, the soil was at its driest in February when Ψ_M was less than -0.35 MPa. In the 2008/09 season the soil became the driest in March when Ψ_M was less than -0.35 MPa (Fig. 3.13). These Ψ_M trends were similar to those observed by Laker (2004) in non-irrigated vineyards in the Western Cape. According to the estimated ET (Table 3.9) and water balance (Table 3.10), most of the available water was depleted in the root zone of the non-irrigated plots during both seasons. However, this does not rule out the possibility that the grapevines could have used water that moved into the root zone by means of capillary from the deeper soil layers. Furthermore, the water balance indicated that the soil was slightly wetter during berry ripening in 2007/08 than in 2008/09. This explained why the Ψ_M in the non-irrigated plots tended to higher in 2007/08 than in 2008/09. The Ψ_M in the single line drip treatment followed the same trend as the non-irrigated one, but Ψ_M was never lower than *ca.* -0.10 MPa (Fig. 3.13). In 2007/08 the threshold for the onset of water constraints occurred during December, whereas in 2008/09 the threshold was already exceeded in November. The lowest Ψ_M for the single drip line was measured in February during both seasons. In the double line drip plots, which received the most irrigation water, Ψ_M remained higher than -0.07 MPa during both seasons (Fig. 3.13). Consequently, grapevines were exposed to readily available water throughout most of the growing season.

In 2007/08, irrigation treatments showed greater differences in Ψ_M than in 2008/09 at Philadelphia in particular with respect to SLD versus DLD (Fig. 3.14). In 2008/09, more differences between non-irrigated and irrigated but no difference between SDL and DLD. As expected non-irrigation resulted in the lowest Ψ_M and the double drip line the highest. In the non-irrigated plot, the threshold for the onset of water constraints occurred in December during both seasons. During the ripening period the Ψ_M remained between -0.09 MPa and -0.17 MPa under the non-irrigated conditions. According to the estimated ET (Table 3.9) and water balance (Table 3.10), more water was available in the root zone of the non-irrigated plots in March during both seasons compared to the non-irrigated plots at Wellington. This difference was primarily due the ET_o being lower in the moderate climate at Philadelphia than in the hot to very hot climate at Wellington. Vineyards with the potential to produce wine of high quality are usually located in climates and soils resulting in water supply being lower than potential evapotranspiration (Pellegrino *et al.*, 2004, and references therein; Seguin, 1983). The water balance indicated that the non-irrigated plot was wetter during berry ripening in 2008/09 than in 2007/08. This difference was the result of higher rainfall in 2008/09 than in 2007/08, and explained why the Ψ_M in the non-irrigated plots tended to be higher in 2008/09 than in

2007/08 (Fig. 3.14). In the irrigated plots, the threshold for the onset of water constraints also occurred in December during both seasons. In the case of the single line drip, Ψ_M was slightly lower than the non-irrigated in December and remained between -0.09 MPa and -0.14 MPa during the 2007/08 ripening period. In the 2008/09 season Ψ_M showed little difference and only varied between -0.06 MPa and -0.10 MPa. In the case of the double drip lines Ψ_M remained at about -0.09 MPa throughout the ripening period in both seasons.

The lowest Ψ_M for the non-irrigated plots was -0.35 MPa for Wellington and -0.17 MPa for Philadelphia. Consequently, grapevines growing in the Wellington plots would be subjected to more water constraints than the ones at Philadelphia. This could be attributed to the hot to very hot climate at Wellington compared to Philadelphia. More water is lost from the soil by evaporation and the soil therefore dries out more rapidly. Since Philadelphia is in a moderate climate, the evaporation losses to the atmosphere are expected to be less. The effect of the irrigation near Philadelphia is reduced by the moderate climate closer to the ocean. Water constraints between flowering and véraison do not modify cell division, but causes irreversible changes in cell enlargement depending on the intensity of the water constraints (Deloire *et al.,* 2005). Since irrigation had a more pronounced effect on soil water status near Wellington, it is expected that there would be more differences in vegetative and reproductive responses of the grapevines at Wellington in comparison to those at Philadelphia.

3.3.4 ROOT DISTRIBUTION AND DENSITY

In general, the root systems were well developed and distributed at both localities (Fig 3.15 & Fig 3.16). Furthermore, the root systems consisted of more fine roots than thicker ones at both localities. A good root system has a high ratio of fine roots to thick roots, since the root system has a higher surface area to absorb water and nutrients (P.A. Myburgh, personal communication). The profile root density did not vary between the plots (Table 3.11), which relates to there being no difference in the physical and chemical soil properties (Table 3.7 & Table 3.8). However, the root distribution percentage was the highest in the subsoil at Wellington, whereas more roots were concentrated in the topsoil at Philadelphia. Root distribution tended to go deeper at Philadelphia compared to Wellington where no roots occurred deeper than 900 mm. This could have caused by physical soil restrictions deeper than 900 mm. However, it should be noted that the environment in which the roots function, e.g.

water and nutrient availability or toxic constraints, will determine the above ground growth. The average root density (Table 3.11) was comparable to 160 roots/m^2 in clay loam soil in Stellenbosch (Hunter, 1998) and 179 roots/m^2 in red sandy soil near Lutzville (Southey & Archer, 1988). Higher root densities of 863 roots/m^2 in sandy loam soil have been found for Sauvignon blanc on 99 Richter in Stellenbosch (Conradie, 2002).

3.4 CONCLUSIONS

On a regional macro climatic scale, the Swartland region is generally classified as having a hot climate. However, on a meso climatic scale the region can be further divided due to the difference in atmospheric conditions. The temperature increases with an increase in distance from the ocean in the Swartland region. Due to proximity to the ocean, RH and wind speed was higher at Philadelphia than Wellington. Solar radiation R_S and rainfall was higher near Wellington compared to Philadelphia. As a result of these differences, climate varied on a meso scale. Hence, two distinct climatic regions could be identified according to climatic indices in this region, namely Wellington and Philadelphia which are 51 km and 12 km, from the Atlantic Ocean respectively. Based on MFT, Wellington was classified as having a hot to very hot climate and Philadelphia as having a moderate climate. This was confirmed by the Winkler index, whereby Wellington and Philadelphia were Class V and Class III, respectively. The IH also confirmed the classification into two temperature classes. The CI however, showed no difference between the localities, which could be explained by the topography and proximity to a large body of water. The total hours for optimal grapevine functioning, *i.e.* 15˚C to 35˚C, measured in the canopy tended to increase closer to the ocean. The unfavourable hours, *i.e.* >35˚C, where grapevine functioning is impeded were higher at Wellington compared to Philadelphia. However, hours above the critical threshold probably did not occur to such an extent that it would have had negative effects on the grapevine functioning.

Since soil chemical and physical properties were comparable at the two sites, it could be eliminated as reasons for causing different grapevine responses. Similarly, comparable soil texture and PAW at the localities could be eliminated as reasons for causing different grapevine responses. Although the soil water holding capacities of the two soils were comparable, it does not rule out the possibility that the volume of irrigation water applied will influence grapevine functioning. When the climate is warmer irrigation could have a more prominent effect on grapevine response than under moderate conditions. Due to the similarity in the soil conditions between the localities, grapevine root densities in the soils at Wellington and Philadelphia were comparable.

3.5 LITERATURE CITED

Acevedo, C., Ortega-Farias, S., Moreno, Y. & Cordova, F. (2004). Effects of different levels of water application in pre- and post-véraison on must composition and wine colour (cv. Cabernet Sauvignon). *Acta Hort.* **664**, 483-489.

Amerine, M.A. & Winkler, A.J. (1944). Composition and quality of musts and wines of California grapes. *Hilgard.* **15**, 493-673.

Anonymous (1989). Climate statistics for the Winter Rainfall Region. Section Agrometeorology, Elsenburg, Soil and Irrigation Research Institute, Dept. Agric. Water Supply. Private Bag X1, Elsenburg.

Bates, T., Dunst, R. Taft, T. & Vercant, M. (2002). The Vegetative Response of 'Concord' Grapevines to soil pH. *HortScience.* **37**, 890-893.

Böhm, W. (1979). Mehtods of studying root systems. Springer – Verlag, Berlin.

Bonnardot, V., Carey, V., Planchon, O. & Cautenet, S. (2001). Sea breeze mechanism and observations of its effects in the Stellenbosch wine producing area. *Wineland*, October 2001, 107-113.

Booysen, J.H., Steenkamp, J. & Archer, E. (1992). Benaming van vertikale prieelstelsels (met afkortings). Wynboer, September 1992, 15.

Campbell-Clause, J.M. (1998). Stomatal response of grapevines to wind. *Austr. J. Exp. Agric.* **38**, 77-82.

Carbonneau, A. & Deloire, A. (2001). Plant organization based on source-sink relationship: new finding on developmental, biochemical and molecular responses to environment, 263-280. In: Molecular Biology & Biotechnology of grapevine, ed. Kluwer Academic Publishers, p. 474.

Carey, V. A., (2001). Spatial characteristic of natural terrior units for viticulture in the Bottelaryberg-Simonsberg-Helderberg winegrowinf area. M.Sc. Agric Thesis. Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Carey, V.A., Bonnardot, V.M.F., Smidt, A. and Theron, J.C.D. (2001). The interaction between vintage, vineyard site (mesoclimate) and wine aroma of *Vitis vinifera* L.cvs. Sauvignon blanc, Chardonnay and Cabernet Sauvignon in the Stellenbosch-Klein Drakenstein wine growing area, South Africa (1996-2000). In: Proc. 26th O.I.V. World Vine & Wine Congress, October 2001, Adelaide, Australia. pp. 139-152.

Carey, V.A. (2005). The use of viticultural terrior units for the demarcation of geographical indications for vine production in Stellenbosch and surrounds. Ph D. Dissertation. Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa. pp 90.

Carey, V.A., Saayman, D., Archer, E., Barbeau, G. & Wallace, M. (2008). Viticultural terroirs in Stellenbosch, South Africa. I. The identification of natural terroirs units. *J. Int. Sci. Vigne Vin*. **42**, 169-183.

Chapman, D.W., Roby, G., Ebeler, S., Guinard, J-X & Matthews, M.A. (2005). Sensory attributes of Cabernet Sauvignon wines made from vines with different water status. *Austr. J. Grape & Wine Research* **11**, 339-347.

Conradie, K. (2002). Grondvorm kan wynstyl grootliks beïnvloed: Cabernet Sauvignon uit Durbanville en Robertson. *Wineland*, November 2002, 107-109.

Conradie, W.J., Carey, V.A., Bonnardot, V., Saayman, D., and Van Schoor, L.H., (2002). Effect of different environmental factors on the performance of Sauvignon blanc grapevines in the Stellenbosch/Durbanville districts of South Africa. *S. Afri. J. Enol. Vitic*. 23, 78-91.

Coombe, B.G. (1987). Influence of temperature on composition and quality of grapes. *Acta Hort.* **206**, 23-33.

Dalla Marta, A., Stefano, V.D., Cerovic, Z.G., Agati, G. & Orlandini, S. (2008). Solar radiation affects grapevine susceptibility to *Plasmopara Viticola*. *Sci. Agric*. **65**, 65-70.

Deloire, A., Vaudour, E., Carey, V., Bonnardot, V. & Van Leeuwen, C. (2005). Grapevine responses to terroir: A global approach. *J. Int. Sci. Vigne Vin.* **39**, 149-162.

De Villiers, F.S., Schmidt, A., Theron, J.C.D. & Taljaard, R. (1996). Onderverdeling van die Wes-Kaapse wynbougebiede volgens bestaande klimaatskriteria. *Wynboer*, January 1996, T10-T12.

Ferrini, F., Mattii, G.B. & Nicese, F.P. (1995). Effect of temperature on key physiological responses of grapevine leaf. *Am. J. Enol. Vitic.* **46**, 375-379.

Gladstones, J. (1992). History of climate selection for Australian viticulture. Viticulture and Environment. Winetitles, Adelaide. p. 4-7.

Greenspan, M. 2008. Row direction - Which end is up? Wine Business Monthly, July 2008, http://www.winebusiness.com/wbm/?go=getArticle&dataId=58458 Date of access: 19 November 2009.

Huglin, P. (1978). New method for evaluating the potential of solar thermal environments wine. In: International Symposium on Ecology of Grapevine, I, Constance, Romania, 1978. Ministry of Agriculture and Food Industry, p. 89-98.

Hunter, J.J., (1998). Plant spacing implications for grafted grapevine I. Soil characteristics, root growth, dry matter partitioning, dry matter composition and soil utilisation. *S. Afr. J. Enol. Vitic.* **19**, 25-34.

Hunter, J.J., Bonnardot, V., (2002). Climatic requirements for optimal physiological processes: A factor in viticultural zoning. In: Proc. 4th Int. Symp. on Viticultural Zoning, 17-20 June 2002, Avignon, France, p.553-565.

Laker, M.S. (2004). The effect of atmospheric and soil conditions on the grapevine water status. M.Sc. Agric Thesis. Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Le Roux, E.G. (1974). A cliamtic categorisation of the South African Western Cape wine producing areas. [Title in Afrikaans: 'n Klimaatsindeling van die Suidwes-Kaaplandse Wynbougebiede]. *M.Sc. Agric Thesis*. Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Myburgh, P.A. (2005a). Water status, vegetative growth and yield responses of *Vitis vinifera* L. *cvs.* Sauvignon blanc and Chenin blanc to timing of irrigation during berry ripening in the Coastal Region of South Africa. *S. Afr. J. Enol. Vitic*. **26**, 59-67.

Myburgh, P.A. (2005b). Effect of altitude and distance from the Atlantic Ocean on mean February temperatures in the Western Cape Coastal Region. *Wynboer Technical Yearbook* 2005, 49-52.

Ojeda, H., Andary, C., Kraeva, E., Carbonneau, A. & Deloire, A. (2002). Influence of pre- and post véraison water deficits on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. *Am. J. Enol. Vitic.* **53**, 261-267.

Planchon, O., Bonnardot, V.M.F., Cautenet, S. & Carey, V.A. (2000). Sea breeze numerical simulation in the Stellenbosch/Drakenstein winegrowing area (4 February 2000). In: Proc. 2nd SASEV International Congress, Cape Town, South Africa, 8 - 10 November 2000, 30.

Pellegrino, A., Lebon, E., Voltz, M. & Wery, J. (2004). Relationship between plant and soil water status in vine (*Vitis vinifera L.). Plant and Soil.* **266**, 129-142.

Saayman, D. (1977). The effect of Soil and Climate on Wine quality. *In: Proc. Int. Sym. Quality of Vintage. 14-21 February 1977, Cape Town, South Africa, 197-208.*

Santalucia, G., Barbagallo, M.G., Costanza, P., Di Lorenzo, R. & Pisciotta, A. (2007). Vegetative and reproductive behavior of *Vitis vinifera* L. (cv. 'Cabernet Sauvignon') vines growing under non-irrigated conditions and moderate water stress induced by different irrigation systems. *Acta Hort.* **754**, 323-328.

Seguin, G. (1983). The influence of vineyard soils on the composition and quality of harvested grapes. *Bulletin de l' OIV.* ***56****, 3-18.*

Soil Classification Working Group. (1991). Soil Classification – A taxonomic system for South Africa. Department of Agriculture Development: Memoirs on natural agricultural resources of South Africa No. 15, Department of Agricultural development, Pretoria, South Africa.

Smart, R. (1985). Principles of grapevine canopy microclimate manipulations with implications for yield and quality. A review*, Am.J. Enol. Vitic.* **36**, 230-239.

Smart, R.E. & Dry, P.R. (1980). A climatic classification for Australian viticultural regions. *Austr. Grapegrower & Winemaker.* **196**, 9-16.

Southey, J.M. and Archer, E. (1988). The effect of rootstock cultivar on grapevine root distribution and density. In: Van Zyl, J.L. The grapevine root and its environment. No. 215. 57-73.

Spayd, S., J. Tarara, D. Mee, and J. Ferguson. (2002). Seperation of sunlight and temperature effects on the composition of *Vitis vinifera cv.* Merlot berries*. Am. J. Enol. Vitic.* **53**,171-182.

Tesic, D., Woolley, D.J., Hewett, E.W., Martind, J. (2002). Environmental effects on cv Cabernet Sauvignon (Vtit vinifera L.) grown in Hawke's Bay, New Zealand.: 2. Development of a site index. *Austr. J. Grape & Wine Research.* ***8****, 27-35.*

Tonietto, J.(1999). Les macroclimates viticole mondiaux et l'influence du mésoclimat sur la typieite de la Syrah et du Muscate de Hambourg dans le sud de la France. Methologie de caracteristion. *PhD Thése, Ecole Nationale Supérieure Agronomique de Montpellier.*

Tonietto, J. & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agric. Forest Meteorology*, Amsterdag **124**, 81-97.

Van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S. & Dubourdieu, D. (2004). Influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic*. **55**, 207-217.

Van Zyl, J.L. (1981). Waterbehoefte en besproeiing. In: Burger, J. & Deist, J. (eds.) Wingerdbou in Suid-Afrika. CTP Boekdrukkers, Cape Town, p. 237-238.

Van Zyl, J.L. (1987). Diurnal variation in grapevine water stress as a function of changing soil water status and meteorological conditions. *S. Afr. J. Enol. Vitic.* **8**, 45-52.

Williams, L.E., Dokoozlian, N.K. & Wample, R. (1994). Grape. In: Shaffer, B & Anderson, P.C. (Eds). Handbook of environmental physiology of fruit crops, Vol I, Temperate crops. CRC Press, Boca Raton, 85-133.

Table 3.1. The locality and soil type of the experiment localities, as well as co-ordinates, altitude, distance from Atlantic Ocean, planting date, root stock, plant spacing and trellis system of Cabernet Sauvignon vineyards in the Swartland region where soil and grapevine water status were monitored during the 2007/08 and 2008/09 seasons.

Locality attributes	**Locality**	
	Wellington	**Philadelphia**
Latitude	33 36' S	33 40' S
Longitude	18 58' E	18 35' E
Altitude (m)	148	132
Distance from Atlantic Ocean (km)	50.9	12.2
Planting date	1992	2000
Root stock	99R	99R
Plant spacing (m x m)	2.5 x 1.5	2.75 x 1.2
Trellis system[(1)]	MP	5LP
Soil type	Glenrosa	Clovelly

[(1)] MP = Moveable Perold and 5LP = Five strand lengthened Perold (Booysen *et al*., 1992).

Table 3.2. Experimental plots in commercial Cabernet Sauvignon vineyards at two localities in the Swartland region where grapevines were subjected to different irrigation systems during the 2007/08 and 2008/09 seasons.

Plot number	**Locality**	**Irrigation system**
WNI	Wellington	Non-irrigated
WSD	Wellington	Single drip line
WDD	Wellington	Double drip line
PNI	Philadelphia	Non-irrigated
PSD	Philadelphia	Single drip line
PDD	Philadelphia	Double drip line

Table 3.3. Monthly irrigation applied to Cabernet Sauvignon in six experiment plots where soil and grapevine water status was monitored at two localities in the Swartland region during the 2007/08 and 2008/09 season.

Season	Locality					
	Wellington			Philadelphia		
	WNI[(1)]	WSD	WDD	PNI	PSD	PDD
			November			
2007/08	-	54	103	-	1.6	3.1
2008/09	-	14	26	-	0	0
			December			
2007/08	-	38	88	-	25	50
2008/09	-	63	122	-	18	36
			January			
2007/08	-	53	101	-	14	28
2008/09	-	45	87	-	22	44
			February			
2007/08	-	64	124	-	9	18
2008/09	-	73	140	-	41	82
			March			
2007/08	-	32	62	-	0	0
2008/09	-	86	164	-	0	0
			Seasonal total (mm)			
2007/08	-	249	478	-	50	99
2008/09	-	281	540	-	81	162

[(1)] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 3.4. Long term daily maximum temperature, daily minimum temperature, mean relative humidity, radiation and mean wind speed measured at two localities in the Swartland region during the 2007/08 and 2008/09 season.

Locality	Month						
	Sept	Oct	Nov	Dec	Jan	Feb	Mar
	Daily maximum temperature (ºC)						
Wellington	20.7	24.9	26.9	29.5	31.8	31.8	31.8
Philadelphia	18.7	23.0	23.6	26.0	27.7	27.9	27.7
	Daily minimum temperature (ºC)						
Wellington	9.4	12.4	14.4	16.4	17.7	17.8	16.8
Philadelphia	9.1	11.6	15.3	15.2	16.5	16.7	15.6
	Mean relative humidity (%)						
Wellington	74.0	75.9	66.8	65.9	64.5	67.8	65.3
Philadelphia	73.9	66.5	64.7	62.4	62.7	63.3	60.5
	Radiation ($MJ/m^2/day$)						
Wellington	16.6	24.1	27.5	30.7	30.6	26.5	19.4
Philadelphia	15.7	21.0	25.6	28.3	29.2	26.9	25.9
	Wind speed (m/s)						
Wellington	2.5	2.7	2.9	2.9	3.0	2.8	2.5
Philadelphia	2.7	2.9	3.8	3.8	4.1	3.7	3.2

Table 3.5. Equations used to convert neutron probe count ratios (CR) to soil water matric potential (Ψ_m) at two localities in the Swartland region during the 2007/08 and 2008/09 season.

Locality	Soil depth (mm)	Equation	R^2	Std. error	*p*
Wellington	0-300	$\Psi_m = -(3.2667-30.6287\ln(CR))^2$	0.9541	0.58	< 0.001
	300-600	$\Psi_m = -(5.4948-30.9471\ln(CR))^2$	0.8737	0.90	< 0.001
	600-900	$\Psi_m = -(4.9162-43.6789\ln(CR))^2$	0.9325	0.63	< 0.001
Philadelphia	0-300	$\Psi_m = -(8.0599-49.2769\ln(CR))^2$	0.9081	0.70	< 0.001
	300-600	$\Psi_m = -(7.5481-46.0229\ln(CR))^2$	0.9068	0.62	< 0.001
	600-900	$\Psi_m = -(17.3695-67.3030\ln(CR))^2$	0.9711	0.38	< 0.001

Table 3.6. Mean February temperature (MFT), Winkler index in terms of growing degree days (GDD), Huglin index (IH) and Cool night index (CI) measured at two localities in the Swartland region during the 2007/08 and 2008/09 season.

Locality	Season				Long term mean	
	2007/08		2008/09			
	MFT (ºC)	**Class**	**MFT (ºC)**	**Class**	**MFT (ºC)**	**Class**
Wellington	24.5	Hot	25.5	Very hot	24.4	Hot
Philadelphia	21.6	Moderate	22.9	Moderate	22.1	Moderate
	GDD	**Class**	**GDD**	**Class**	**GDD**	**Class**
Wellington	2375.0	V	2353.5	V	2421.1	V
Philadelphia	1833.1	III	1867.6	III	1983.2	IV
	IH	**Class**	**IH**	**Class**	**IH**(1)	**Class**(1)
Wellington	2833.2	IH5	2854.9	IH5	-	-
Philadelphia	2314.4	IH4	2371.7	IH4	-	-
	CI	**Class**	**CI**	**Class**	**CI**	**Class**
Wellington	16.8	IF2	16.8	IF2	16.8	IF2
Philadelphia	15.5	IF2	16.4	IF2	15.6	IF2
	Tn	**Tx**	**Tn**	**Tx**	**Tn**	**Tx**
Wellington(2)	13.0	26.0	12.9	24.6	17.8	31.8
Philadelphia(2)	13.0	23.6	13.7	23.4	16.7	27.9

(1) Long term means could not be calculated.
(2) Minimum (Tn) and maximum (Tx) temperature one month before harvest.

Table 3.7. Estimated stone fraction, particle size distribution, textural class and plant available water (PAW) in the soils in Cabernet Sauvignon vineyards in the Swartland region during the 2008/09 season.

	Locality					
	Wellington			Philadelphia		
Soil Depth (mm)	**0-300**	**300-600**	**>600**	**0-300**	**300-600**	**>600**
Stone (Vol %)	4.1	2	1.65	0.1	0	0
Clay (%)	13.8	17	18.6	18.8	14.8	16.8
Silt (%)	12	12.8	14.1	8	6.2	8
Fine sand (%)	41.7	39.2	40.8	52.8	56.3	52.1
Medium sand(%)	16	13.6	14.0	16.4	18.4	17.9
Coarse sand (%)	16.5	17.4	12.5	4.0	4.2	5.2
Soil texture(1)	SaLm	SaLm	SaLm	SaLm	SaLm	SaClLm
PAW (mm/m)	112	113.7	116.95	127.4	129.2	125.5

(1)Sa = sand, Lm = loam & Cl = clay.

Table 3.8. Soil chemical analyses in the Cabernet Sauvignon vineyards in the Swartland region during the 2008/09 season.

	Locality					
	Wellington			Philadelphia		
Soil Depth (mm)	**0-300**	**300-600**	**>600**	**0-300**	**300-600**	**>600**
pH_{KCl}	6.0	5.3	5.2	6.3	5.4	5.3
Ec (dS/m)	11.34	4.78	6.34	23.00	16.47	20.05
C (%)	0.5	0.4	0.3	0.3	0.1	0.3
P (mg/kg)	36	28	15	13	10	11.5
K (mg/kg)	39	51	71	159	46	50
Na_{ex} (cmol(+)kg)	0.00	0.01	0.08	0.46	0.24	0.30
K_{ex} (cmol(+)kg)	0.10	0.13	0.18	0.41	0.12	0.13
Ca_{ex} (cmol(+)kg)	1.30	0.81	1.27	2.67	2.20	2.04
Mg_{ex} (cmol(+)kg)	0.29	0.25	0.14	0.86	0.73	0.96
Cu (mg/kg)	3.1	4.2	1.7	5.1	3.5	3.1
Zn (mg/kg)	3.0	1.9	0.8	1.0	0.5	0.4
Mn (mg/kg)	5.0	12.3	5.6	113.4	116.6	115.3
B (mg/kg)	0.4	0.2	0.1	0.7	0.5	0.4
Fe (mg/kg)	67.0	112.4	149.5	237.6	126.9	43.0

Table 3.9. Crop coefficients (K_c), reference evapotranspiration (ET_o) and estimated evapotranspiration (ET) of non-irrigated Cabernet Sauvignon vineyards monitored at two localities in the Swartland region.

Month	K_c [(1)]	Wellington			Philadelphia		
		ET_o (mm/d)	ET (mm/d)	ET (mm/month)	ET_o (mm/d)	ET (mm/d)	ET (mm/month)
September	0.58	2.3	1.3	39.3	1.9	1.1	33.1
October	0.45	4.0	1.8	55.2	3.2	1.4	44.4
November	0.29	5.5	1.6	47.6	4.4	1.3	38.3
December	0.33	6.3	2.1	64.4	5.1	1.7	52.2
January	0.13	6.7	0.8	25.8	5.5	0.7	21.2
February	0.11	6.5	0.7	19.5	4.9	0.5	14.8
March	0.11	4.8	0.5	16.0	3.8	0.4	12.8
September until March (mm)				267.9			216.7

[(1)] K_c values obtained from Laker (2004).

Table 3.10. Evapotranspiration (ET), plant available water (PAW), rainfall from September until March and the estimated resulting water balance of non-irrigated Cabernet Sauvignon vineyards monitored at two localities in the Swartland region.

Locality	Season	ET (mm/d)	PAW (mm/m)	Rainfall (mm)	PAW + Rainfall – ET (mm)
Wellington	2007/08	267.9	116	163	11
	2008/09	267.9	116	152	0
Philadelphia	2007/08	216.7	127	116	26
	2008/09	216.7	127	151	61

Table 3.11. Root distribution of the Cabernet Sauvignon grapevines quantified at the end of the two year experimental trial 2008/09 seasons at two localities in the Swartland region.

	Locality							
	Wellington				Philadelphia			
Soil depth (mm)	**0-300**	**300-600**	**600-900**	**>900**	**0-300**	**300-600**	**600-900**	**>900**
Root numbers	101	230	198	0	361	123	89	25
Root distribution (%)	19.1	43.5	37.4	0.0	60.4	20.6	14.9	4.2
Profile density (roots/m^2)	174.93				166.11			

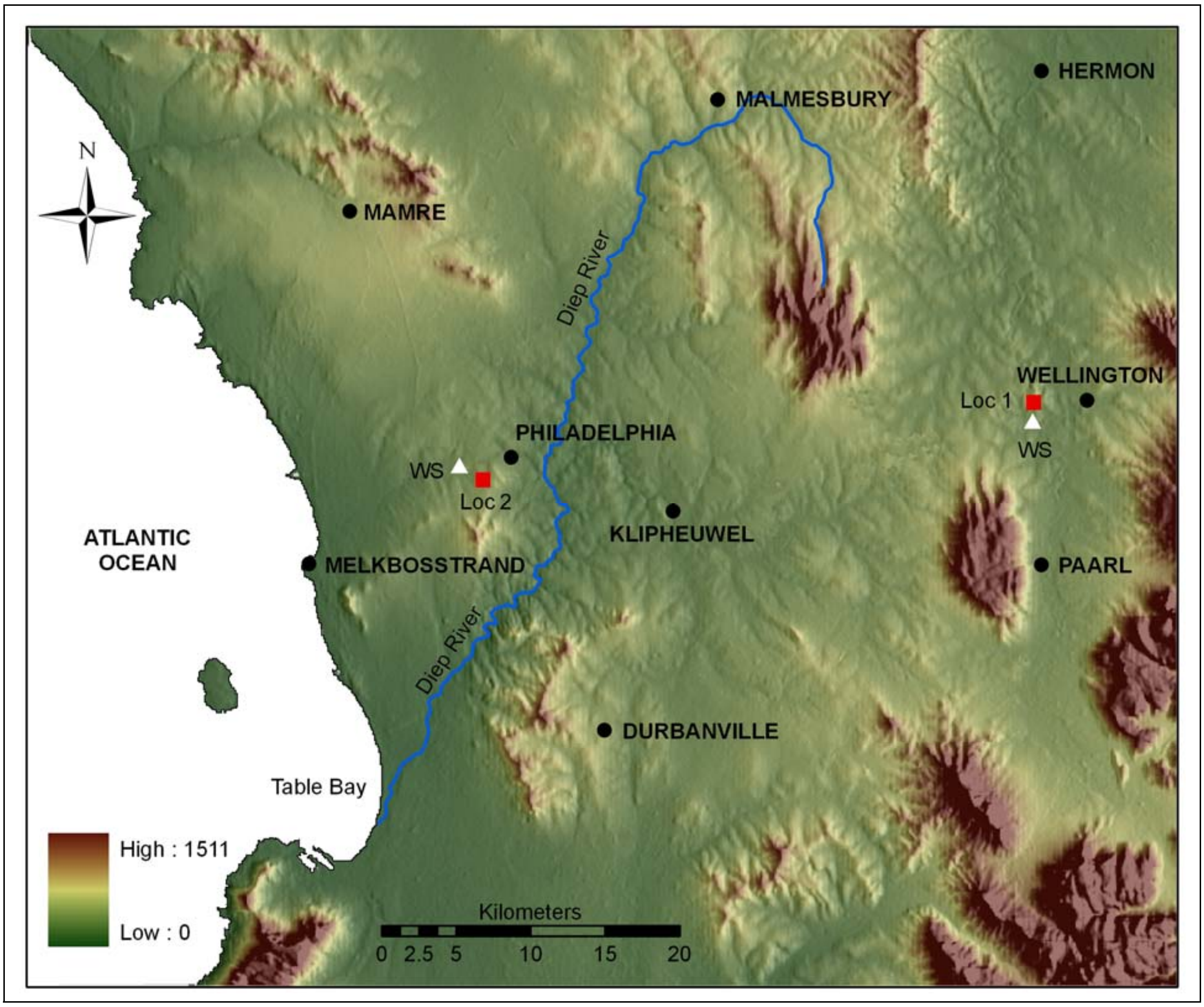

Figure 3.1. The localities of the two Cabernet Sauvignon vineyards and weather stations (WS) near Wellington (LOC 1) and Philadelphia (LOC 2) in the Swartland region.

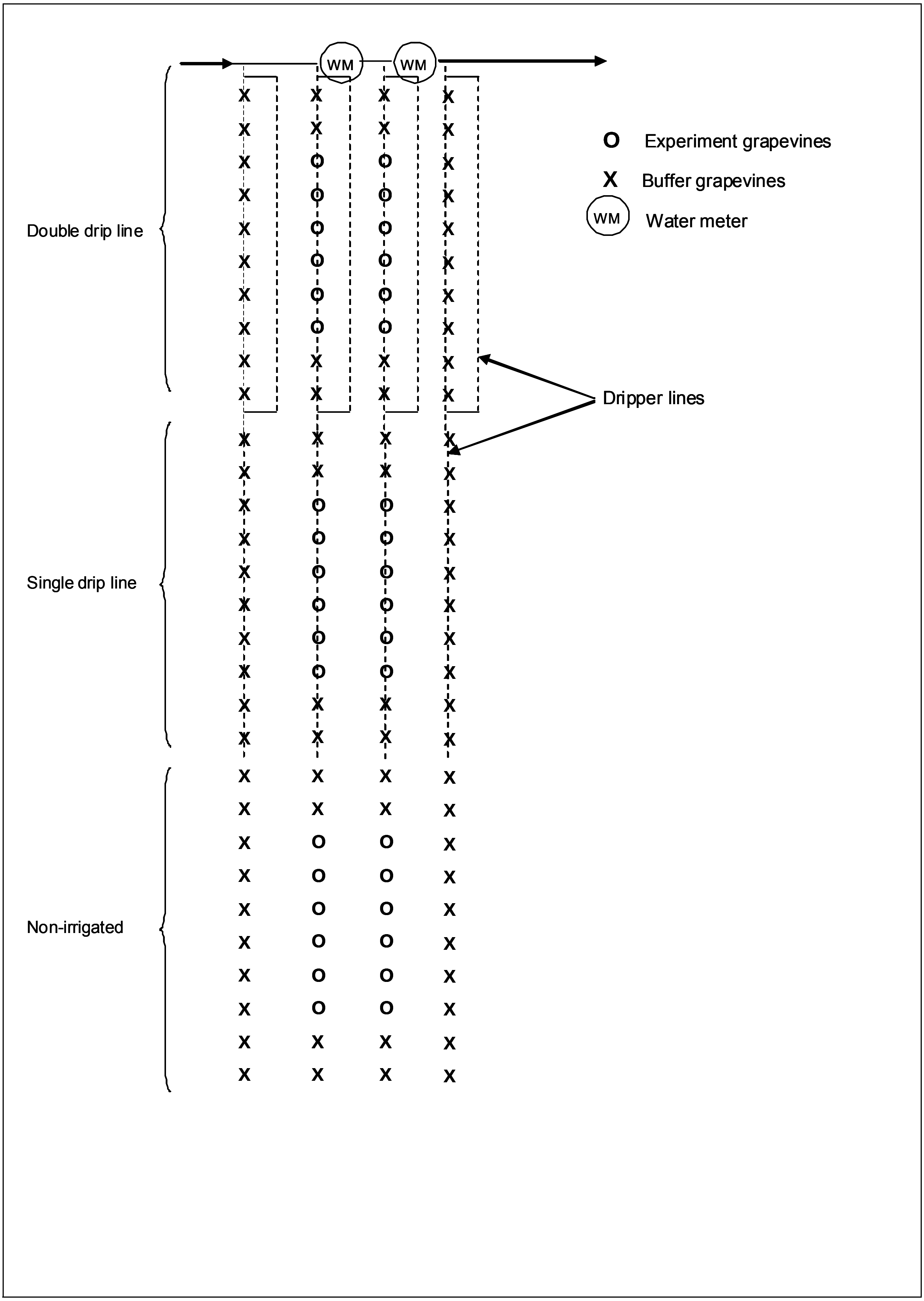

Figure 3.2. Schematic diagram of the experiment plot layout in Cabernet Sauvignon vineyards in the Swartland region where soil and grapevine water status were monitored during the 2007/08 and 2008/09 seasons.

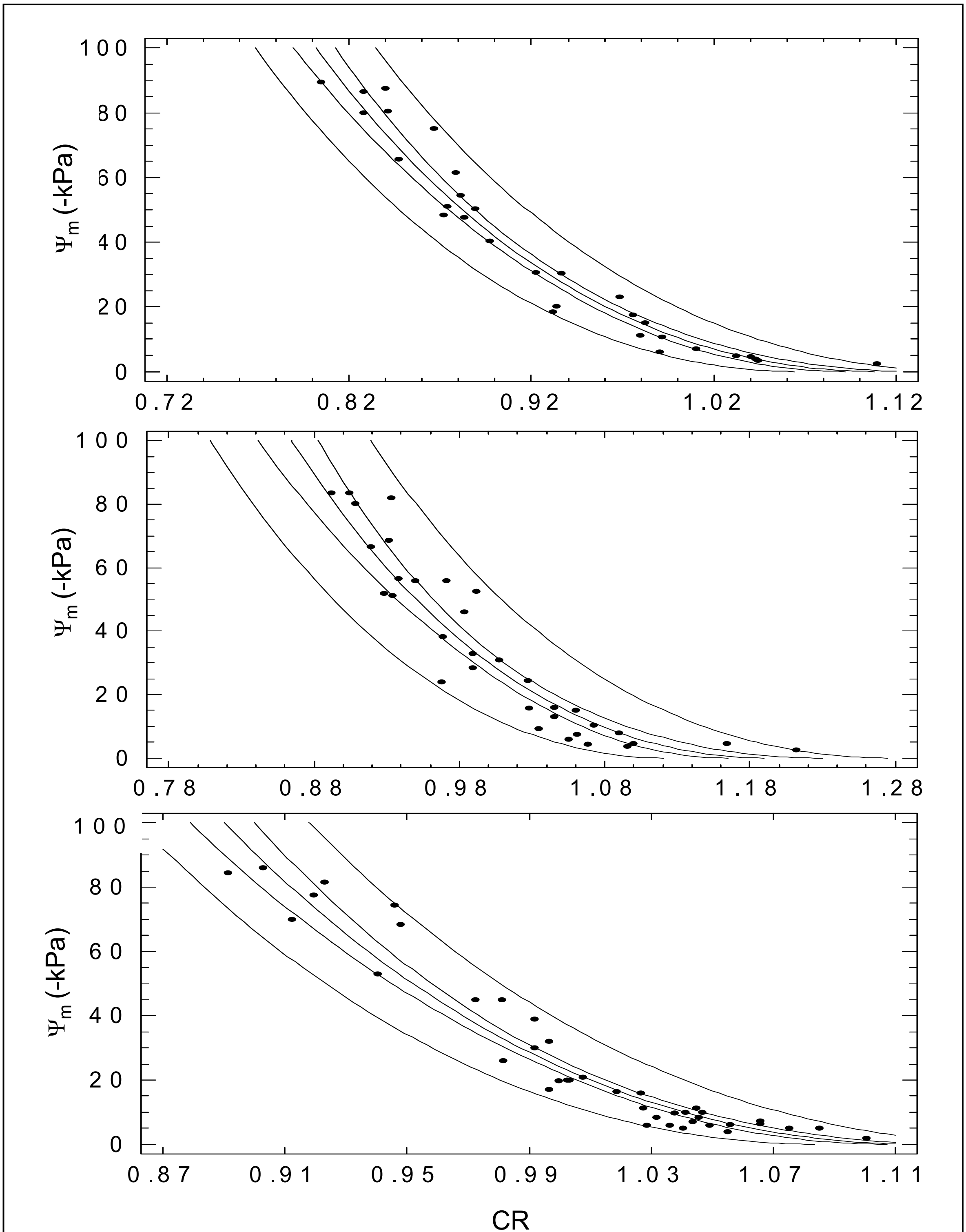

Figure 3.3. Soil water matric potential (Ψ_m) *vs* neutron probe count ratio (CR) determined for (A) 0 to 300 mm, (B) 300 mm to 600 mm and (C) 600 mm to 900 mm depth increments in a sandy clay loam soil near Wellington. Refer to Table 3.5 for the regression equation details.

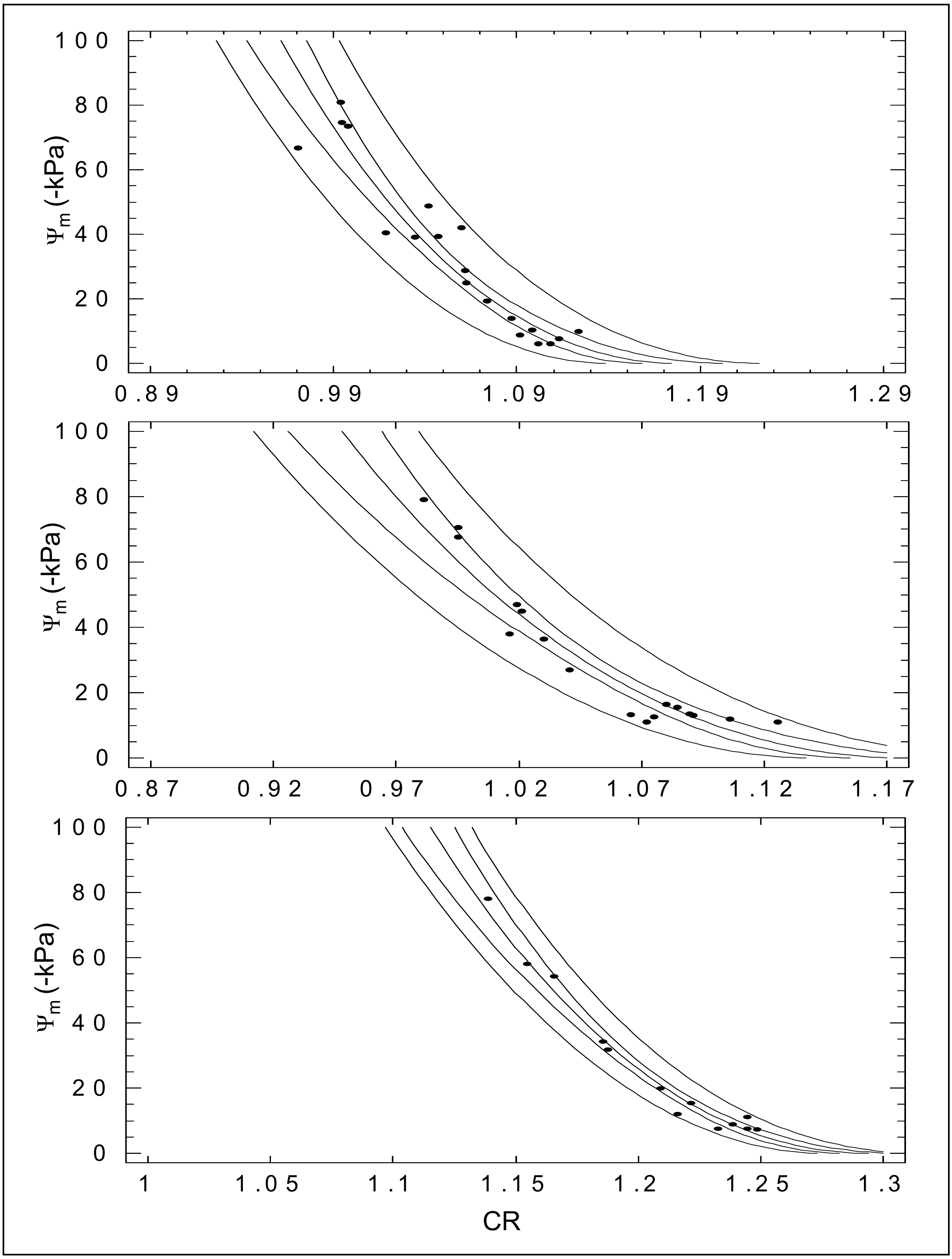

Figure 3.4. Soil water matric potential (Ψ_m) *vs* neutron probe count ratio (CR) determined for (A) 0 to 300 mm, (B) 300 mm to 600 mm and (C) 600 mm to 900 mm depth increments in a sandy clay loam soil near Philadelphia. Refer to Table 3.5 for the regression equation details.

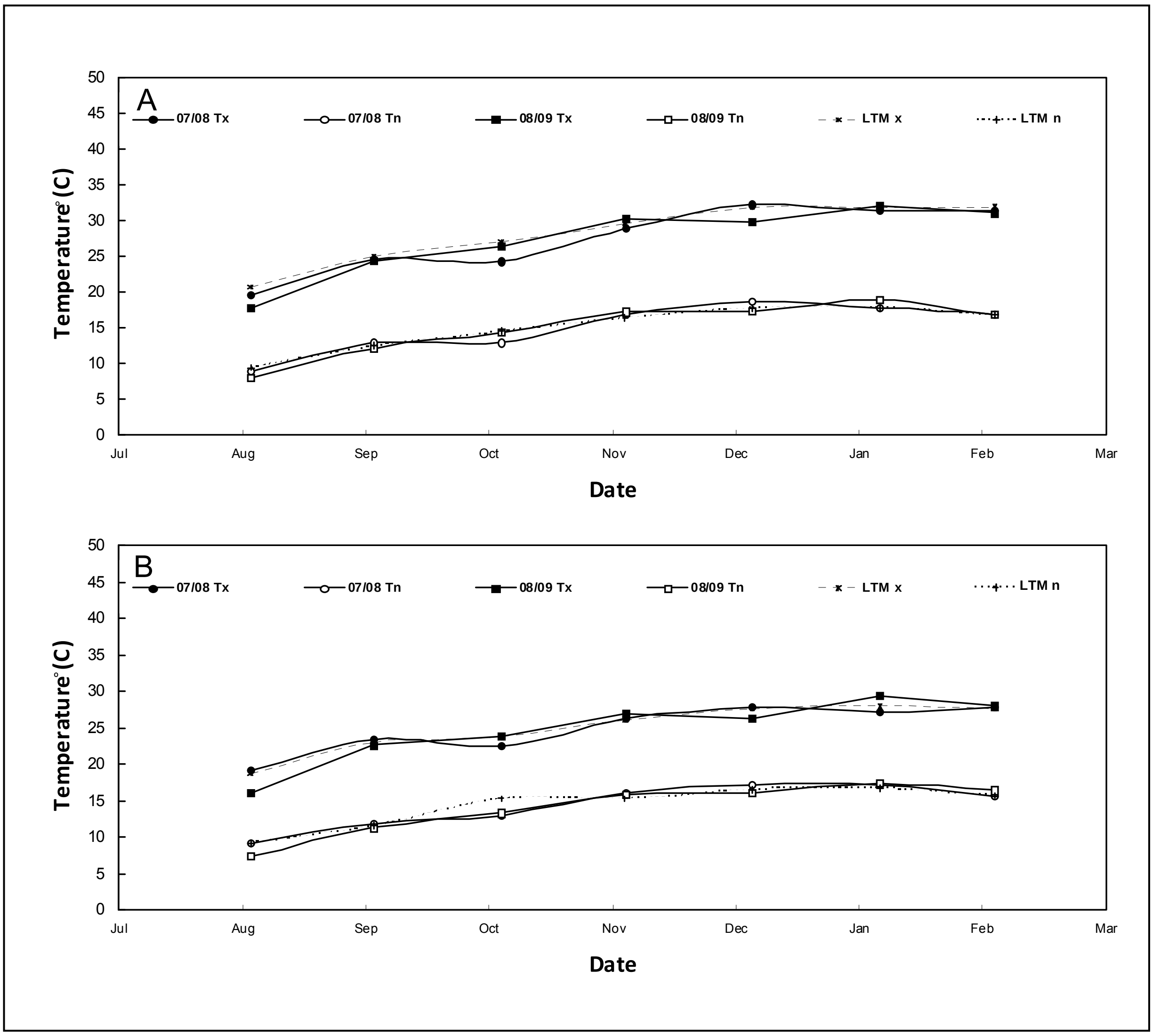

Figure 3.5. Mean monthly maximum (Tx) and minimum (Tn) temperatures compared to the long term mean (LTM) at (A) Wellington and (B) Philadelphia during the 2007/08 and 2008/09 seasons.

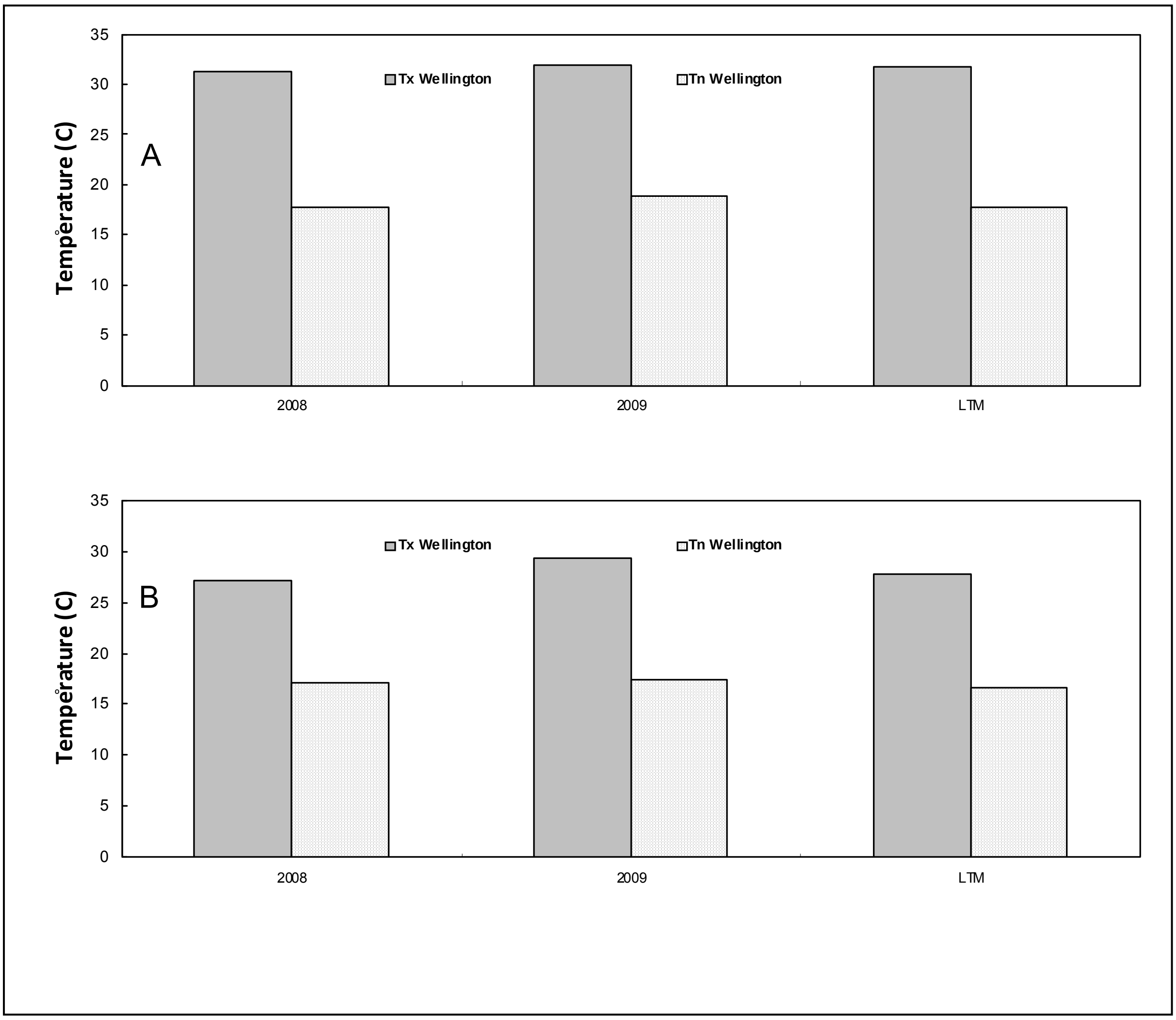

Figure 3.6. Mean maximum (Tx) and minimum (Tn) temperature trends one month before harvest at (A) Wellington and (B) Philadelphia during the 20007/08 and 2008/09 seasons.

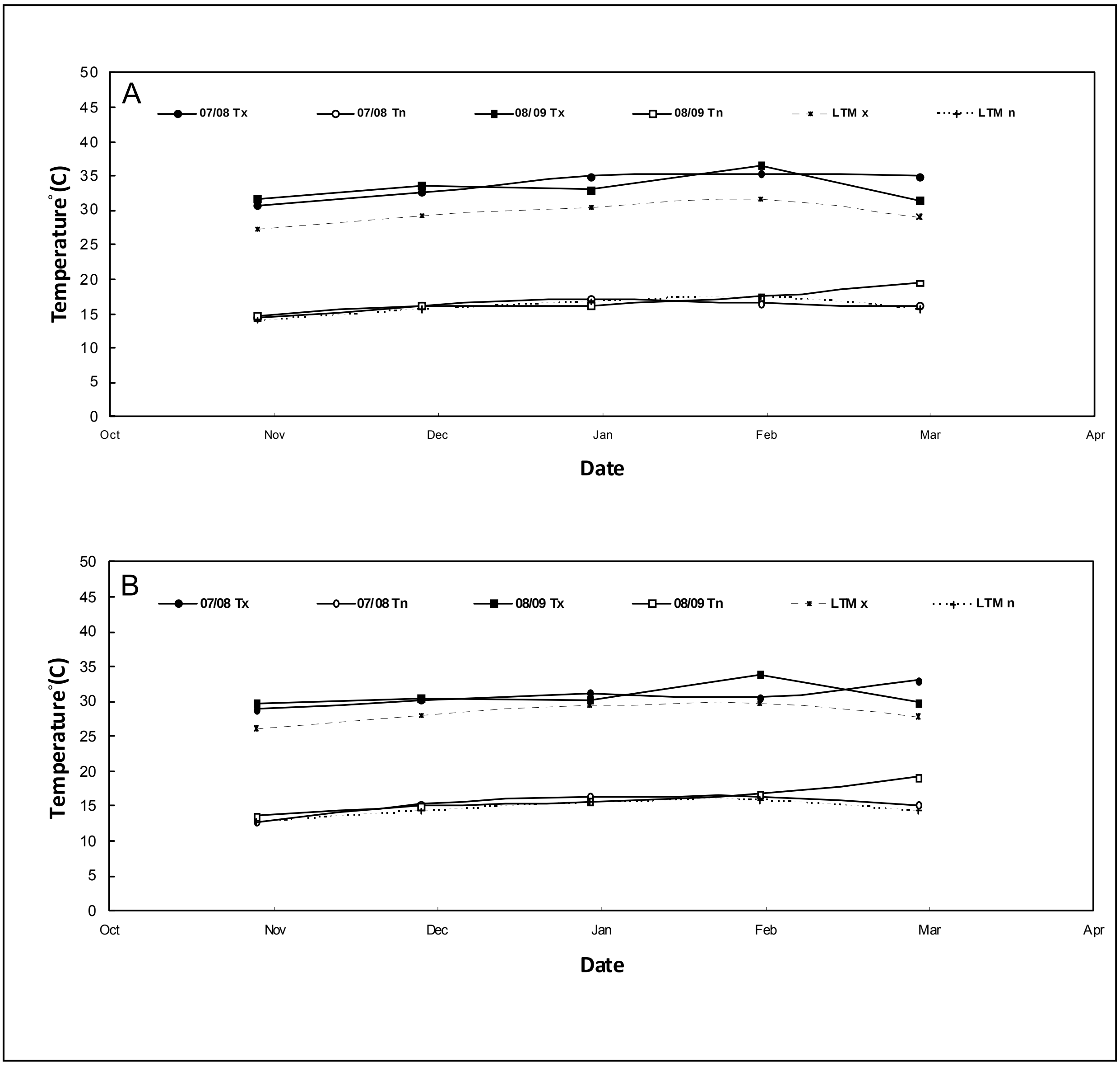

Figure 3.7. Mean monthly maximum (Tx) and minimum (Tn) temperature in grapevine canopies compared to the long term mean (LT) air temperature at (A) Wellington and (B) Philadelphia during the 20007/08 and 2008/09 seasons.

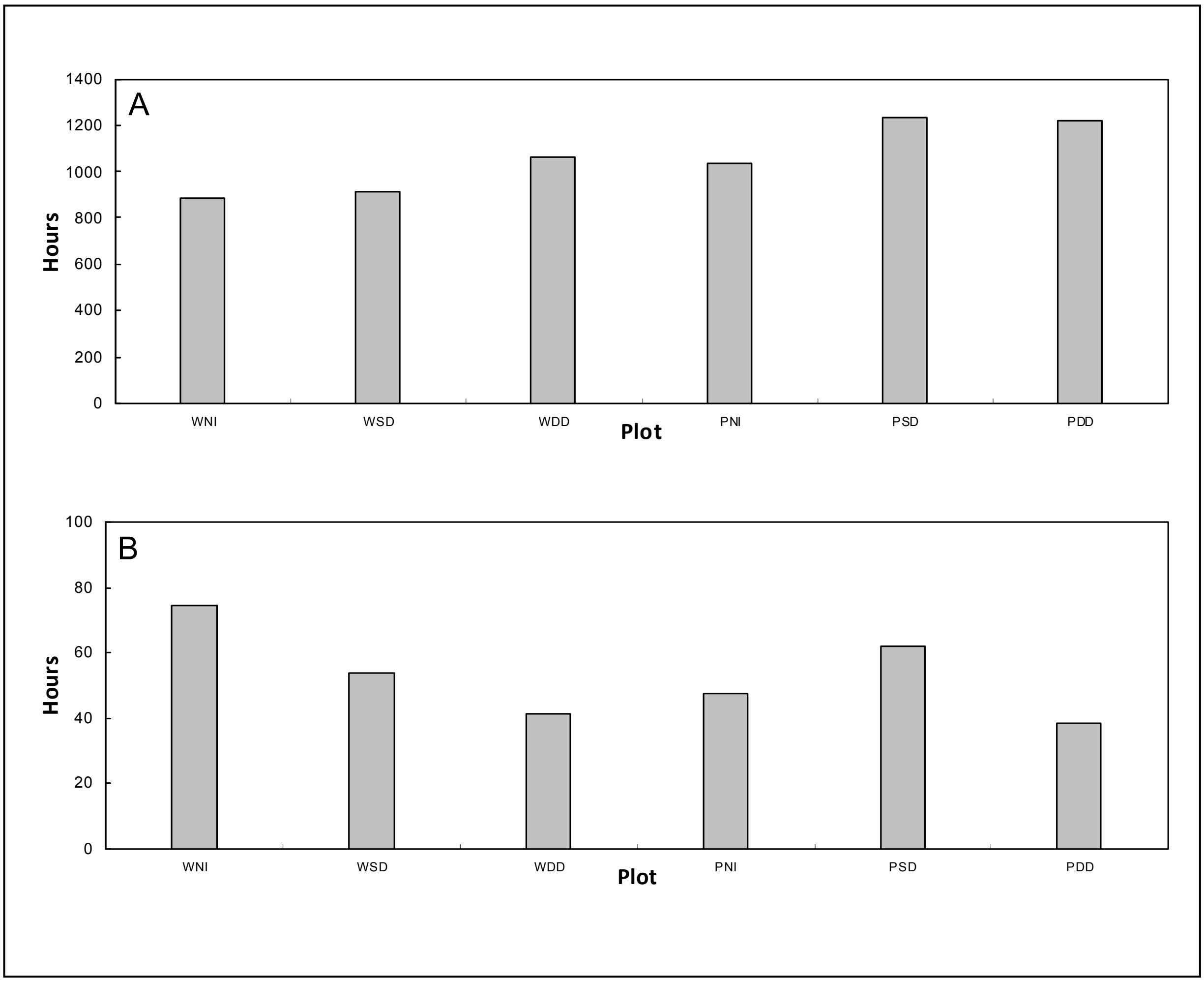

Figure 3.8. Total hours for (A) optimum grapevine functioning, *i.e.* 15ºC to 35ºC and (B) a decline in grapevine functioning, *i.e.* >35ºC accumulated from the first week in January to harvest for each plot in the 2009 ripening season. Refer to Table 3.2 for description of plots.

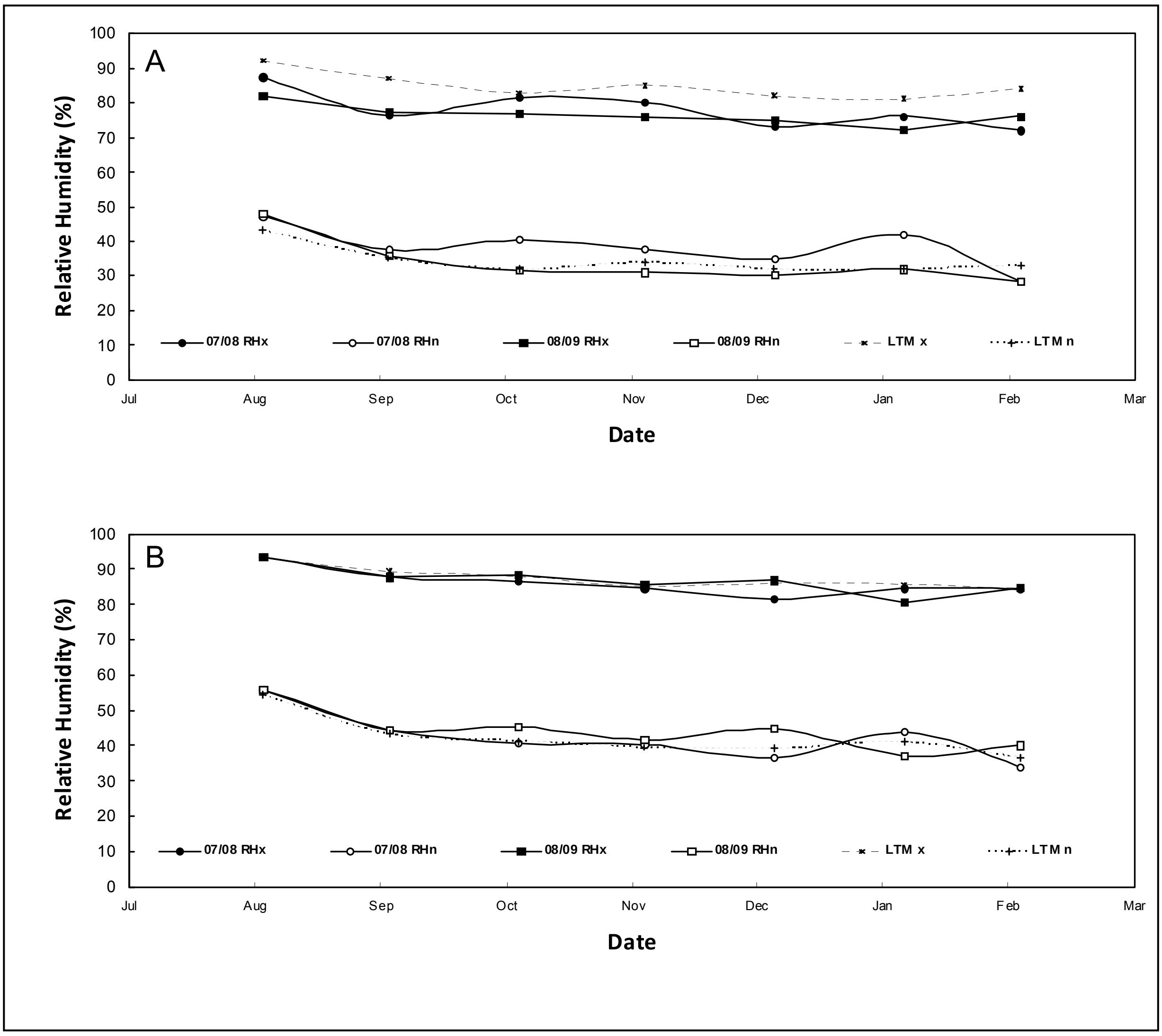

Figure 3.9. Monthly mean maximum and minimum relative humidity in the 2007/08 and 2008/09 growing seasons at (A) Wellington and (B) Philadelphia, compared to the long term values for the Swartland region.

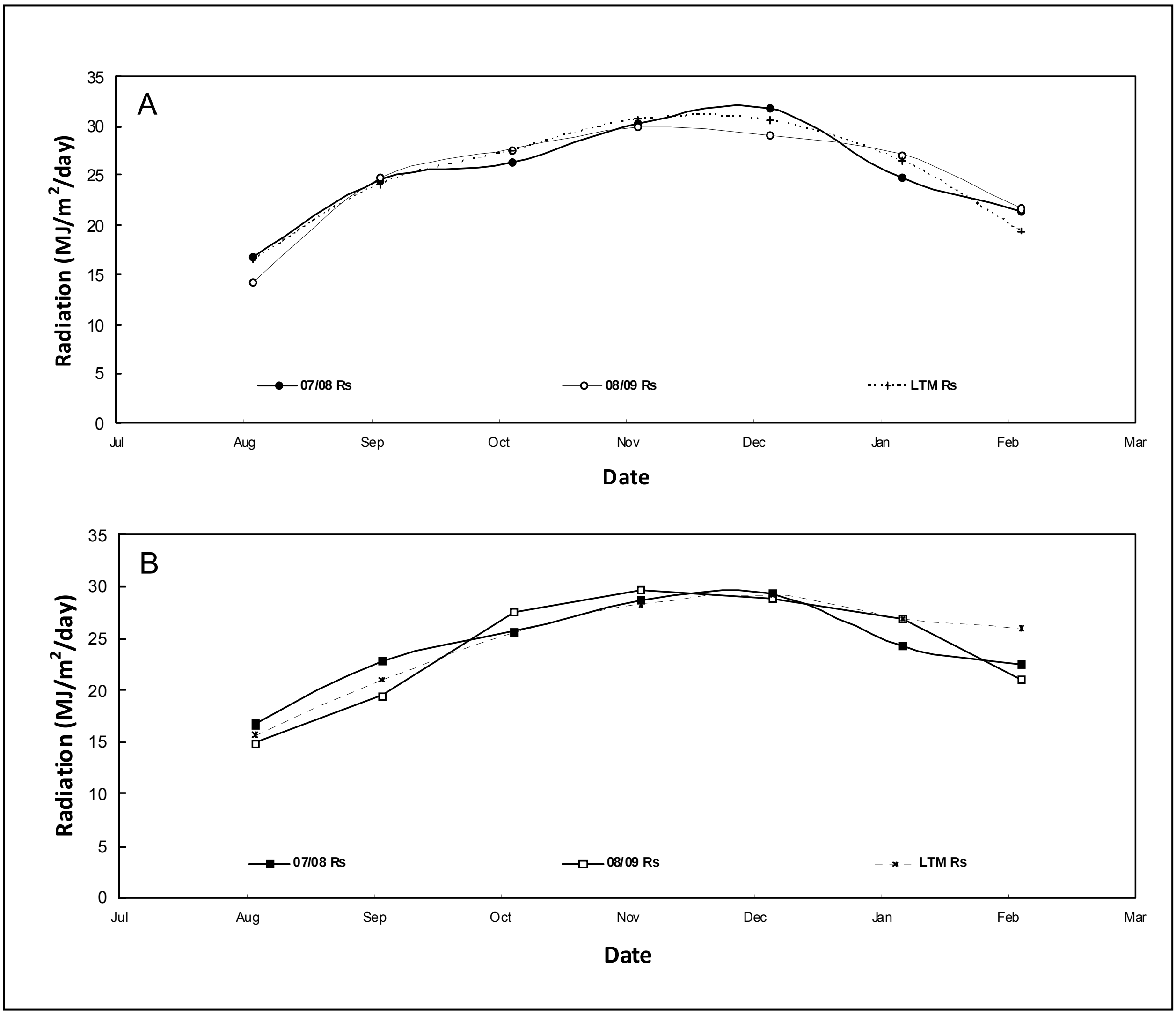

Figure 3.10. Solar radiation at (A) Wellington and (B) Philadelphia in the 2007/08 and 2008/09 growing seasons compared to the long term values for the Swartland region.

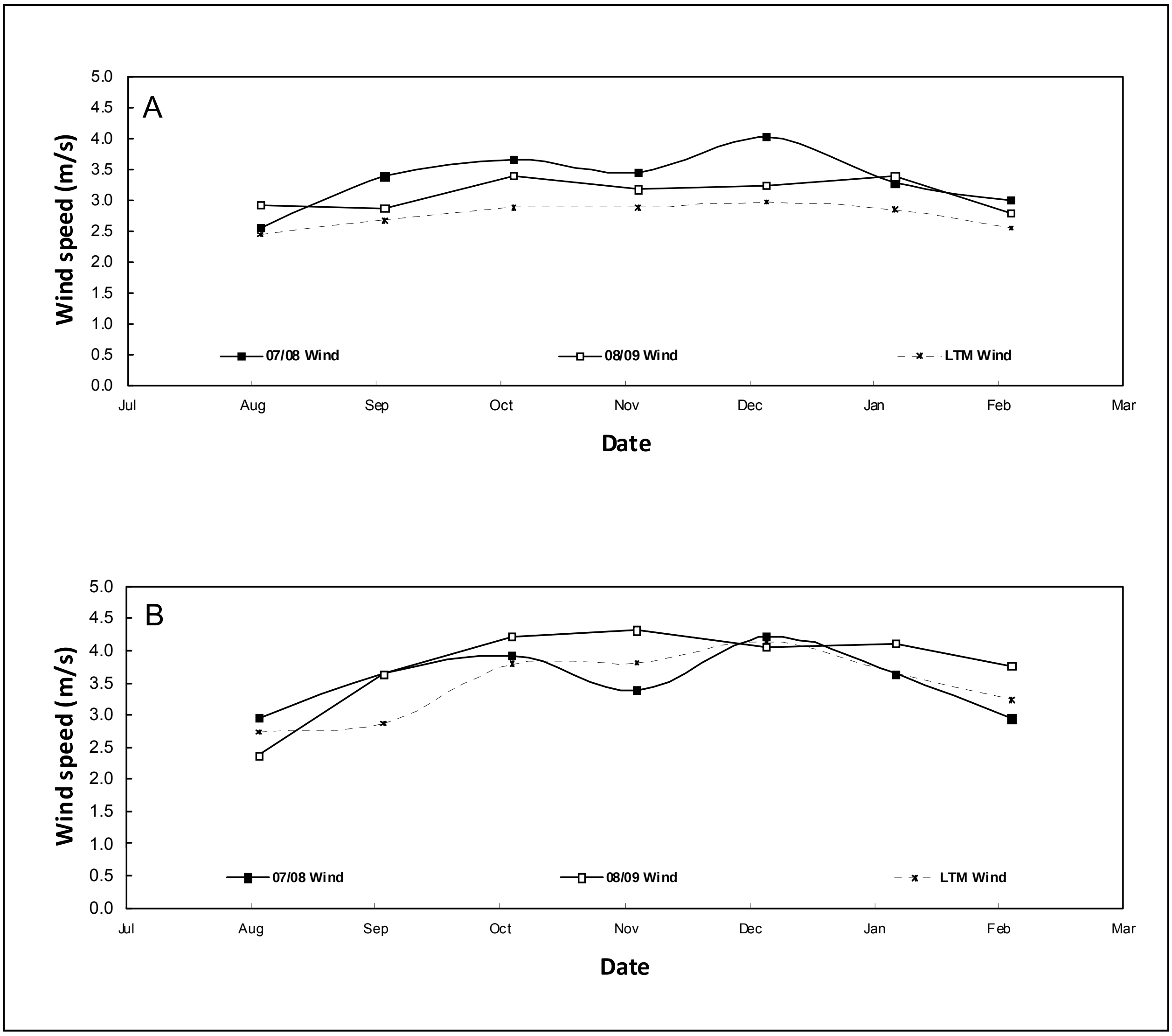

Figure 3.11. Average wind speed at (A) Wellington and (B) Philadelphia in the 2007/08 and 2008/09 growing seasons compared to the long term values for the Swartland region.

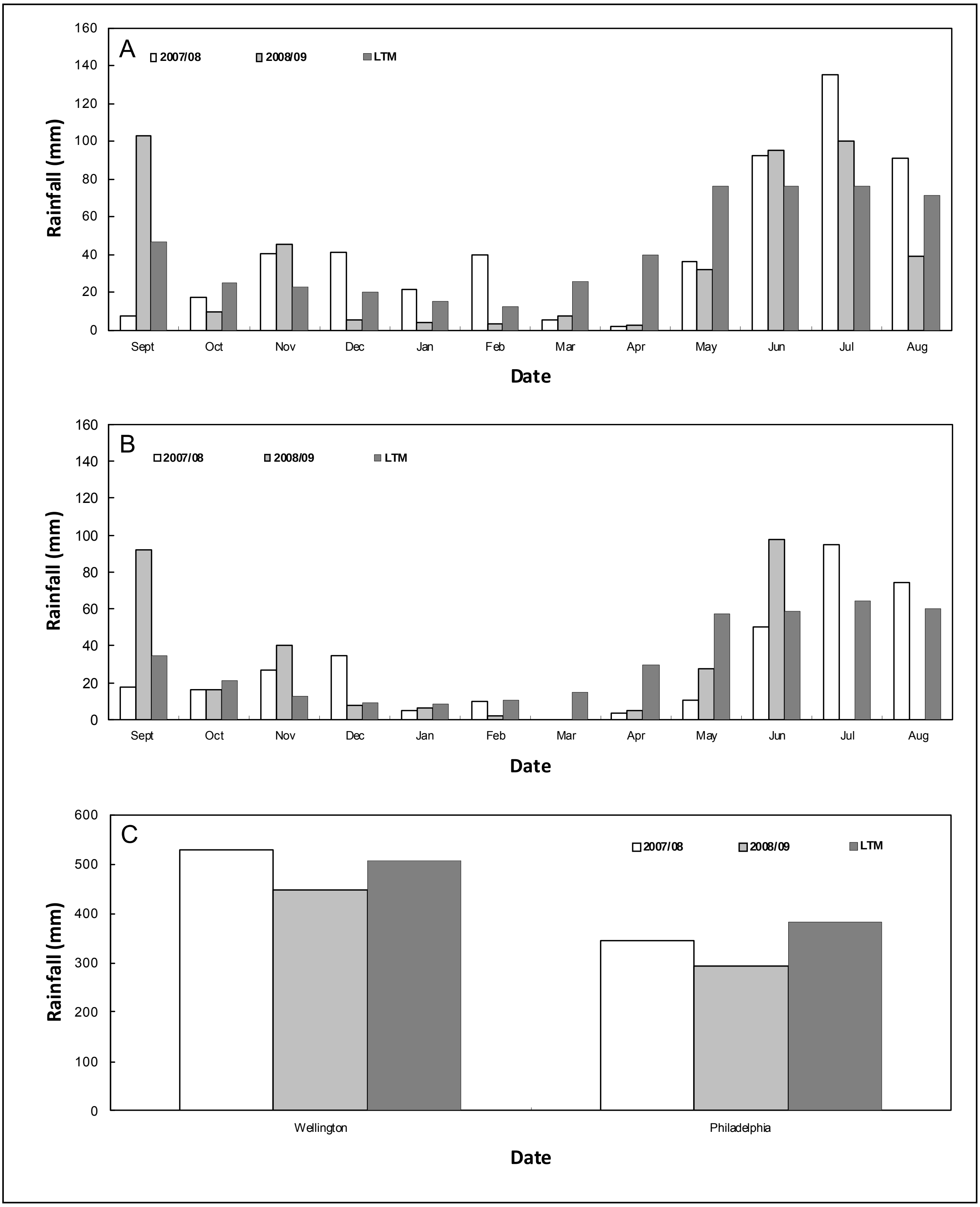

Figure 3.12. Mean monthly rainfall at (A) Wellington and (B) Philadelphia measured during the 2007/08 and 2008/09 seasons in comparison to the long term mean values, and (C) the annual rainfall at each locality.

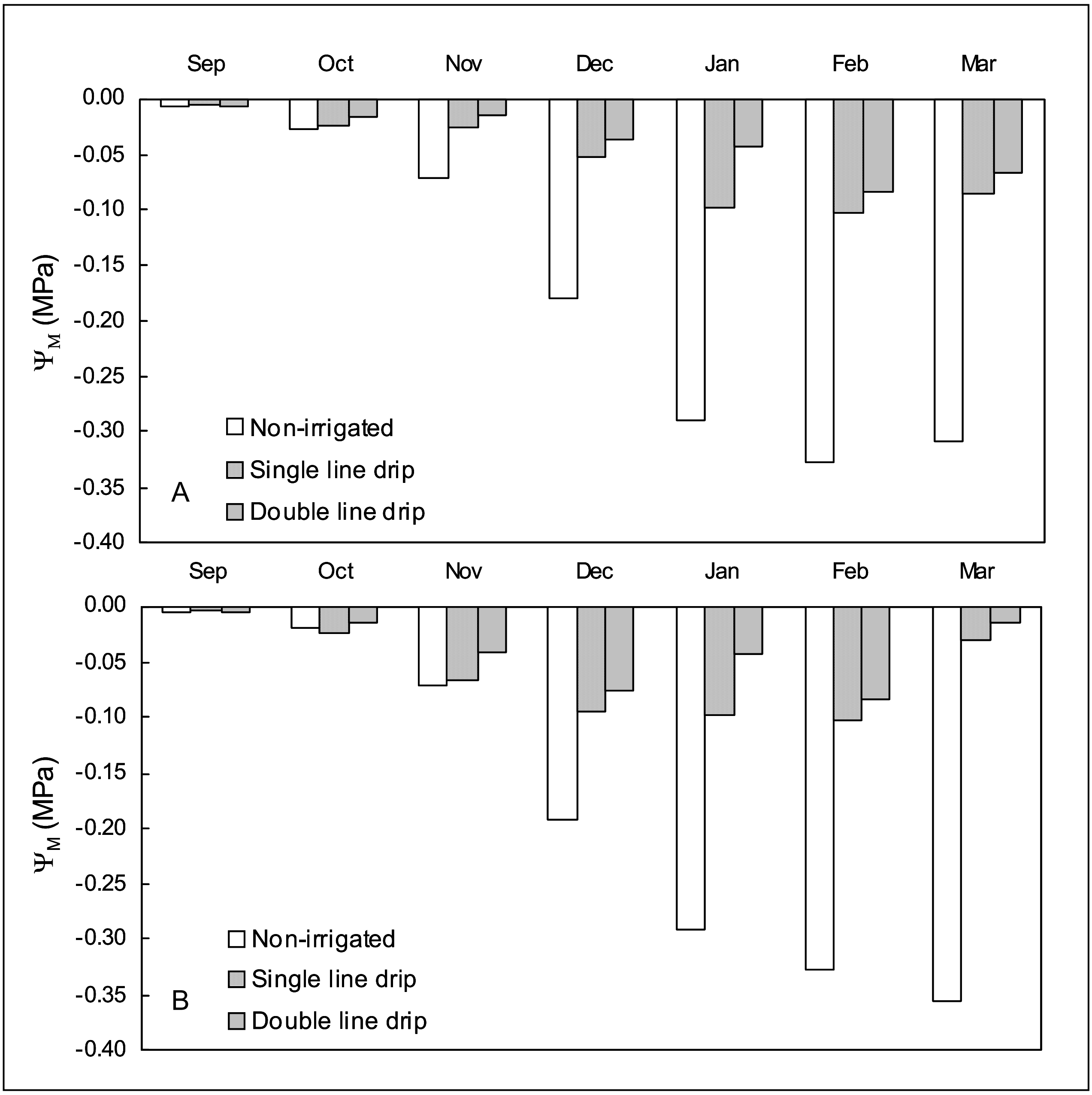

Figure 3.13. Variation in soil water matric potential (Ψ_M) in experiment plots where non-irrigated conditions and two irrigation systems were used to induce different levels of water constraints in Cabernet Sauvignon grapevines at Wellington during the (A) 2007/08 and (B) 2008/09 seasons.

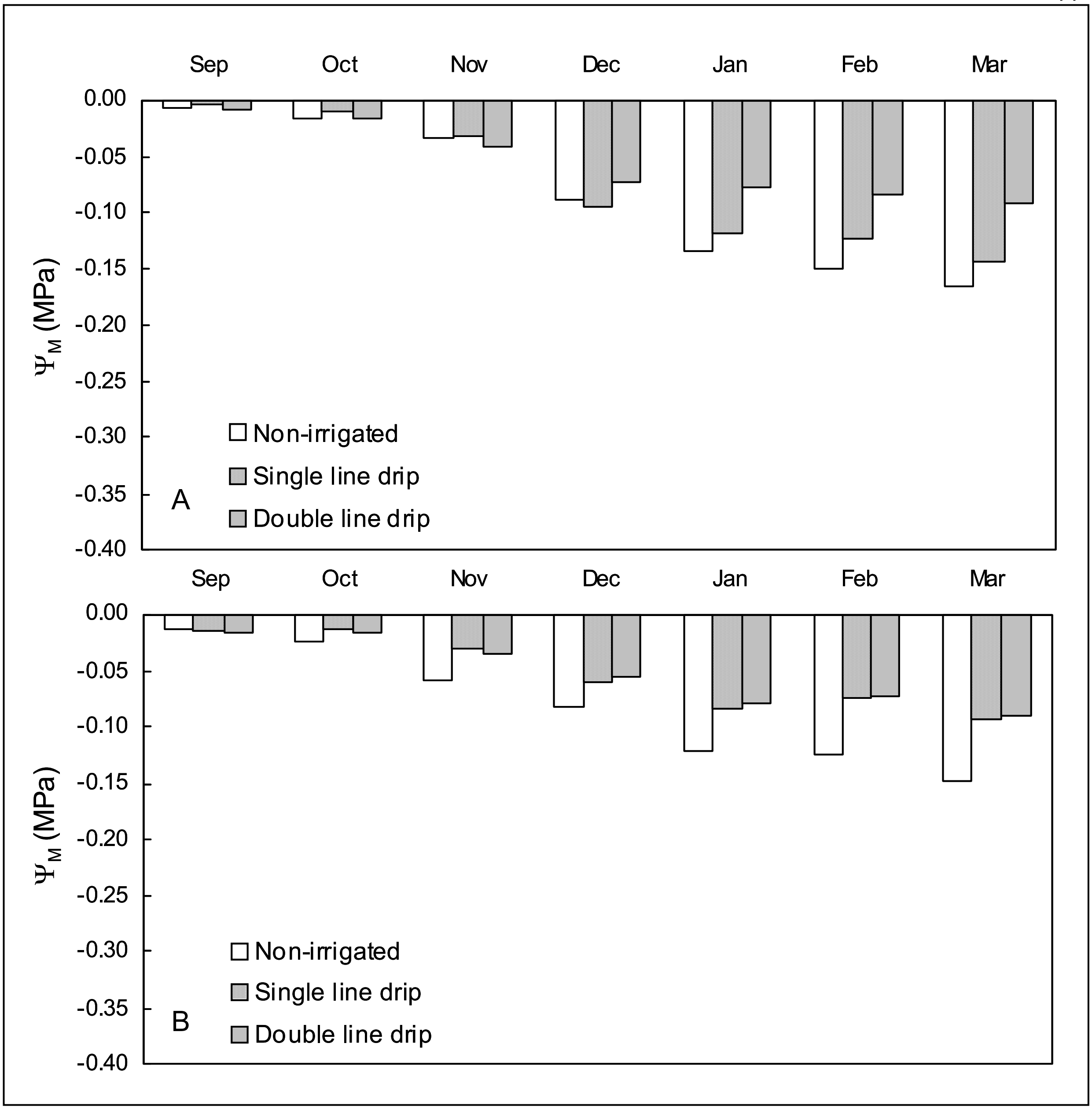

Figure 3.14. Variation in soil water matric potential (Ψ_M) in experiment plots where non-irrigated conditions and two irrigation systems were used to induce different levels of water constraints in Cabernet Sauvignon grapevines at Philadelphia during the (A) 2007/08 and (B) 2008/09 seasons.

Figure 3.15. Example of 99Richter root distribution in a Glenrosa soil form (*i.e.* Orthic A horizon/Lithocutanic B horizon) at Wellington.

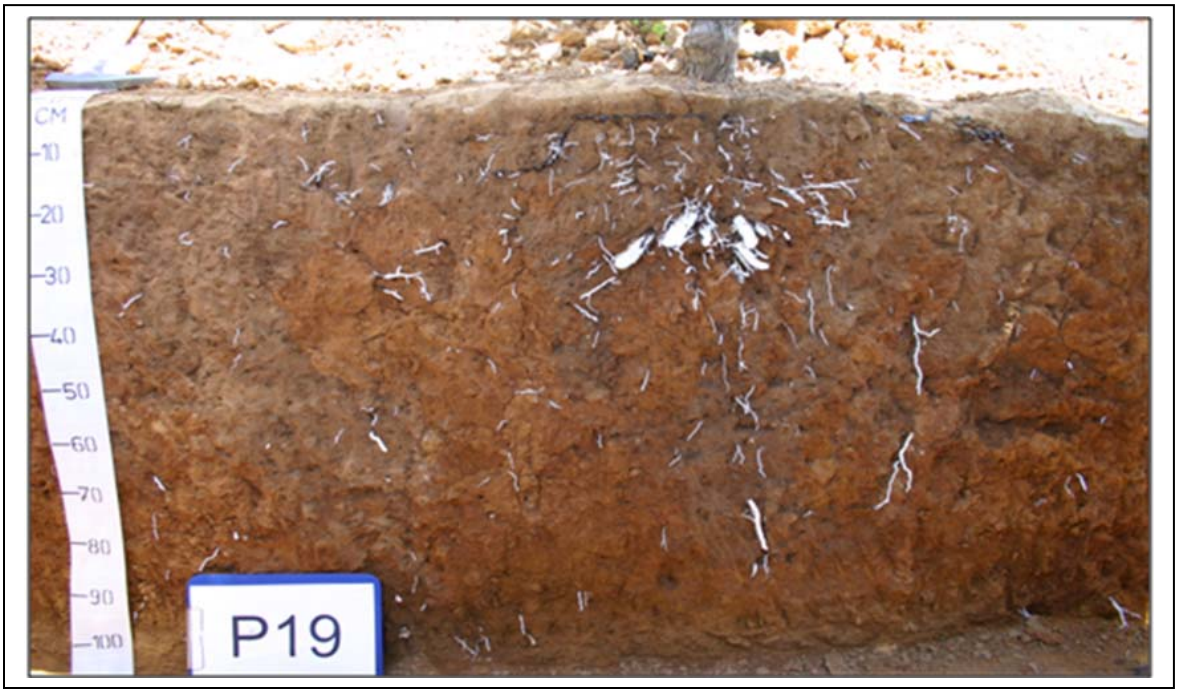

Figure 3.16. Example of 99Richter root distribution in a Clovelly soil form (*i.e.* Orthic A horizon/Yellow brown Apedal B horizon/unspecified material) at Philadelphia.

Chapter 4

RESEARCH RESULTS

EFFECT OF CLIMATE AND SOIL CONDITIONS ON WATER STATUS, VEGETATIVE GROWTH AND YIELD OF CABERNET SAUVIGNON GRAPEVINES (*Vitis Vinifera* L.) AT TWO LOCALITIES IN THE SWARTLAND REGION

EFFECT OF CLIMATE AND SOIL CONDITIONS ON WATER STATUS, VEGETATIVE GROWTH AND YIELD OF CABERNET SAUVIGNON GRAPEVINES (*VITIS VINIFERA* L.) AT TWO LOCALITIES IN THE SWARTLAND REGION.

4.1 INTRODUCTION

The central role of grapevine water status involves the soil water supply and the sunlight interception in relation to the plant architecture and climate (Deloire *et al.,* 2005). Grapevine water status has an effect on grapevine development and grape composition as water constraint accelerates growth cessation of the grapevine (Van Leeuwen *et al.,* 2004). The soil water storage capacity and therefore, ultimately the plant available water is determined by the soil and average root depth, soil texture and structure (Van Zyl, 1981). Water homeostasis has adaptive significance as it enables the plant to perform well under water constraints (Winkel & Rambal, 1993). It is well known that the effect of soil on grapevine behavior is mediated through varying water content levels and therefore effecting grapevine water status (Choné *et al.,* 2001). Water deficits occur when transpiration exceeds the ability of the grapevine root system to supply water to the transpiring leaves (Choné *et al.,* 2001).

Stomatal conductance is regulated to control water deficit and maintain leaf water potential at a constant value (Choné *et al.,* 2001 and reference therein). Stomatal regulation provides a powerful mechanism assuring a high conductivity for water through the whole plant throughout the day (Winkel & Rambal, 1993). The grapevine stomata are closed before sunrise and the plant is therefore in equilibrium with its environment, with the soil water potential and the moist humid layer of soil (Bogart, 2006). Hence, predawn (Ψ_{PD}) leaf water potential is a sensitive indicator of the soil water availability. However, it has been shown that Ψ_{PD} can underestimate the actual grapevine water constraint during the day as the soil water content is very variable (Améglio *et al*., 1999). Nevertheless, Ψ_{PD} can still be used as a reliable technique to determine the grapevine water status, even where the soil available water is easily measured by a neutron probe or a time domain reflectometry (TDR) probe (Deloire *et al.,* 2005). Carbonneau (1998) proposed threshold values for water status classification based on Ψ_{PD} measurements (Table 4.1).

During the day, leaf water potential (Ψ_L) in exposed leaves reflects the combination of many factors interacting with the leaf and grapevine, such as the local leaf water demand, soil water availability, internal plant hydraulic conductivity and stomatal regulation (Choné *et al.,* 2001). Greenspan (2005) proposed threshold values for water status classification based on Ψ_L measurements (Table 4.2). Leaf water potential is considerably more variable depending on the local climate. The stem water potential (Ψ_S) is measured in a non transpiring leaf and is the result of whole plant transpiration and soil hydraulic conductivity. This measurement indicates the capacity of the grapevine to conduct water from the soil to the atmosphere (Choné *et al.,* 2001). Stem water potential is less variable than leaf and predawn water potential as it is less susceptible to fluctuations in the environment. Midday Ψ_S exhibited higher significant differences between differently treated grapevines (Choné *et al.,* 2001). Consequently, it was concluded that Ψ_S is most important of the three water potentials, whilst Ψ_L is the least important ($\Psi_S > \Psi_{PD} > \Psi_L$). Van Leeuwen *et al*., (2009) proposed threshold values for water status classification based on Ψ_S, Ψ_L and Ψ_{PD} water potential measurements carried out in France (Table 4.3).

The reference method most commonly used today is the measurement of Ψ_{PD}, which is carried out before sunrise while the stomata of the grapevine are still closed, and when the grapevine has been able to equilibrate its water potential with the soil. Although Ψ_{PD} is considered to a reliable indicator of grapevine water status, it can under estimate the grapevine water constraints during the following day as the soil water content is heterogeneous (Deloire *et al.,* 2005). The pressure chamber technique (Scholander *et al.,* 1965) is a reliable and repeatable method for determining plant water status in field grown grapevines (Greenspan, 2005). This method estimates the capacity of the plant to retain water by pressuring a leaf in a pressure chamber using neutral gas and determining the pressure required to release water from the petiole. The less free water there is in the plant, the greater the pressure that will be required to exude it. The results are expressed as negative values in bar or mega Pascal (MPa).

Reduction in shoot growth is one of the first visible symptoms of grapevine water constraints (Williams, 2000). Cabernet Sauvignon is regarded as a vigorous, low yielding grapevine cultivar (De Villiers, 1986). With more vigorous grapevines, the leaves are larger and shoots longer, therefore there is increased shading. A higher leaf area to canopy surface confirms this. Studies conducted by Smart *et al.* (1985) showed that the leaf area showed a two-fold increase from low to high vigour experimental plots. However, the leaf area to fruit mass ratio was not effected. High must and wine pH, as well as K content, were positively correlated with shading in canopies, while the total ionized anthocyanins and phenol concentrations were negatively correlated with shading (Smart *et al.,* 1985). There is also a degradation of leaf and fruit micro climates and disease development as the canopy density increases with less constraint (Deloire *et al.,* 2004). Highly constrained grapevines on the other hand can inhibit the vegetative growth (Deloire *et al.,* 2005). Therefore, it is essential to manage water supply and soil water availability in vineyards for the optimization of grape and wine quality. This requires the application of moderate plant constraint (Pellegrino *et al.*, 2004).

When a plant lacks water its stomata closes because of a lack of turgidity in the guard cells (Van Zyl, 1986). Transpiration and evaporative uptake of energy is hereby reduced, causing the leaf temperature to rise. Van Zyl (1986) studied the effect of irrigation on the canopy temperature of the Colombar grapevines, which were either subjected to drying cycles or to a well watered control of Colombar. It was shown that there was a decrease in transpiration rate due to water constraints causing the canopy temperature to be warmer than the non-constrained control. Canopy temperature was also linearly correlated with soil water content. Furthermore, the study showed that the onset of grapevine water constraints occurred when the plant available water (PAW) level was between 30% and 60%. The canopy temperatures of constrained grapevines were 1.16˚C to 1.62˚C higher than in well watered control ones (Van Zyl, 1986). The leaf temperature can therefore be used as an indicator of grapevine water constraints.

Grapes respond in two ways to water deficits, namely an indirect and positive response due to a concentration effect (smaller berries) and a direct response on phenolic biosynthesis (Ojeda *et al.*, 2002). This can either be positive or negative depending on the duration and intensity of water deficit. At the beginning of berry development, the green active berries are very sensitive to water deficit treatments (Van der Westhuizen, 1972; Williams, 2000). Low levels of water constraints could cause excessive vigour and dilution of the berry metabolites (Deloire *et al.,* 2004). Mild water deficits are known to have positive effects on reducing berry size and on anthocyanin and tannin content (Choné *et al.,* 2001 and references therein). Under mild water deficits, vegetative growth is no longer in competition with reproductive growth. The berries are therefore the primary sinks during ripening. The size of the berry at harvest indirectly affects the phenolic concentration of the must and concentration depends on the skin surface-to-berry volume ratio (Ojeda *et al.,* 2002, and references therein). The application of moderate to severe water constraints applied from flowering to véraison irreversibly modified Shiraz berry size (Ojeda *et al.,* 2001). Van Leeuwen *et al.* (2004) obtained similar results when grapevines experiencing water deficits prior to véraison resulted in reduced berry size. Highly constrained grapevines, on the other hand, can reduce or inhibit berry growth, photosynthesis and berry maturation (Deloire *et al.,* 2005). Therefore, it is essential to manage water supply and soil water availability in vineyards for the optimization of grape and wine quality. This requires the application of moderate plant constraints (Pellegrino *et al.*, 2004).

The different climatic regions in the Lower Olifants River did not seem to have any effect on the vegetative growth and yield of Cabernet Sauvignon grapevines (Bruwer, 2010). Approximately 79% of the variation in vegetative growth, quantified in terms of pruning mass, could be related to the soil chemical and physical conditions, *i.e.* the soil organic carbon content, soil texture and the water supply to the grapevine. The vegetative growth of normal irrigated grapevines in sandy soils was *ca.* 60% lower compared to normal irrigated grapevines in sandy loam soils. The grapevines in sandy soils were more sensitive to water deficit compared to the grapevines in the sandy loam soils (Bruwer, 2010). Deficit irrigation tended to reduce berry size, irrespective of soil texture. Water constraints in grapevines in sandy soils, early in season at flowering, could reduce the number of berries per bunch which will reduce the grapevine yield. Deficit irrigation reduced yield of grapevines in the sandy soils by *ca.* 30%, whereas, yields of grapevines in heavier soils was only *ca.* 15% lower (Bruwer, 2010). Deficit irrigation could be applied in heavier sandy loam solid to decrease berry size without substantially reducing yield, therefore saving 80% water from flowering to harvest, and improving wine quality with slightly smaller berries. However, reducing water by 50% in sandy soils from flowering to harvest reduced the yield by 30% and these losses were not economically viable. The main driver for differences in vegetative growth and yield seemed to be the difference in soil texture which determined the water supply to the grapevine (Bruwer, 2010).

The aim of this study was to determine the effect of climate, soil and irrigation on grapevine water status, vegetative growth and yield of Cabernet Sauvignon at two localities in the Swartland region of the Western Cape.

4.2 MATERIALS AND METHODS

4.2.1 EXPERIMENT LAYOUT

The grapevine water status was manipulated with the application of water. In this study, grapevine water constraints were induced at the two localities in the Swartland region, *i.e.* one at Wellington (W) and one at Philadelphia (P), to study the interactive effect of proximity to the ocean and soil water content. Details of the experiment and plot layout, as well as soil and viticultural aspects are presented in Chapter 3. In the first plot, grapevines were cultivated non-irrigated (NI), whereas the second plot was irrigated with a single dripper line (SD) in the grapevine row. The third plot was irrigated with two dripper lines (DD), one in the grapevine row and the other in the middle of the work row. Irrigation was applied according to the grower's normal irrigation schedule.

4.2.2 PLANT WATER STATUS

Mid day Ψ_L and Ψ_S were measured by means of the pressure chamber technique (Scholander *et al*., 1965) three times during the berry ripening period on normal, full sunshine days. These measurements were carried out on 21 January, 7 and 19 February 2008 as well as 15 and 28 January and 10 February 2009. Measurements of Ψ_L and Ψ_S were taken at the two localities simultaneously, ensuring the Ψ_L and Ψ_S were recorded in all plots within an hour, *i.e.* between 12:00 and 13:00. Three mature, fully expanded and sun exposed leaves were used from each treatment plot for the Ψ_L. Stem water potential was measured in three mature leaves which had been bagged in aluminium foil at least an hour before measurement. The bagging of the leaves reduced the natural transpiration of the leaf and eliminated light, allowing Ψ_L of the bagged leaf to come into equilibrium with Ψ_S (Bogart, 2006). The leaves for the Ψ_L and Ψ_S were cut with a sharp blade and inserted into the pressure chamber within seconds.

To quantify hourly changes in Ψ_L, diurnal cycles were measured once from 04:00 to 02:00 the next day during the second season. These measurements were carried out post véraison, *i.e.* 28 January 2009, on all treatment plots. For the hourly diurnal $\Psi_{L,}$ three mature, fully expanded and exposed leaves were picked from three different grapevines per plot. Leaf water potential values recorded at 04:00 were considered to representative of Ψ_{PD}.

4.2.3 VEGETATIVE MEASUREMENTS

Leaf area was measured at véraison in all the plots. Ten shoots per plot were selected in a sampling manner that was unbiased. This was achieved by marking an elastic band at five fixed intervals. This band was then suspended along the length of the six experiment grapevines and a shoot sampled at each of the fixed intervals. This was done for both rows to obtain a total of ten shoots. The shoots were stored in plastic bags to maintain integrity of the leaves directly after removal from the grapevines and were refrigerated until measurements were carried out. Leaf surface area was determined using an electronic leaf surface area meter (Delta T device Ltd, Cambridge, UK). Lateral and secondary shoots were separated from the main shoot. The lengths of all shoot were measured and the number of lateral and secondary shoots determined. Leaves were separated into main, lateral and secondary leaves. For the purpose of this study, the secondary growth will be referred to as the lateral growth on the laterals. All the leaves representing a leaf population of the shoot were put through the leaf area meter to quantify the respective leaf areas per shoot. Data obtained was used to calculate the vegetative response of the grapevine canopies to water constraints in each plot.

Shoot mass at pruning was weighed using a hanging balance scale in the vineyards. This served as a quantification of the total vegetative growth in each plot in response to the water constraints. The total number of shoots on each grapevine was counted. In addition, the average numbers of fruiting canes on each spur position were counted. The leaf area per grapevine was calculated by dividing the calculated shoots per grapevine by the total leaf area per shoot. The leaf area index was calculated by dividing the leaf area per grapevine by the row spacing.

4.2.4 REPRODUCTIVE MEASUREMENTS

Grapes were harvested by hand and all bunches were counted using a mechanical counter. The objective was to harvest all grapes at a target of 24˚B. However, due to logistical constraints this was not always possible. The grapes were weighed in the vineyard on a portable balance to determine the mass of grapes harvested per plot. Mean yield per grapevine was calculated from the total mass and converted to tons per hectare. Bunch mass was calculated by dividing the total grape mass per plot by the number of bunches counted per plot. The number of bunches per grapevine was calculated by dividing the total number of bunches per plot by the number of grapevines in the treatment plot. Berry mass was also determined at harvest. Ten bunches were selected randomly at each plot. From these ten bunches, berries were sampled along the longitudinal axis of the bunch. Ten berries on each side of the bunch were sampled to obtain a total of 20 berries per bunch. Berries were removed by cutting through the pedicle as close as possible to the berry, using a small pair of scissors. The 200 berries per plot were weighed and used to calculate the average mass per berry.

4.2.5 STATISTICAL ANALYSES

Analysis of variance (ANOVA) was used to test the effects of locality and irrigation strategy on grapevine response. Relationships between variables were determined by means of linear regression at the 95% confidence level using Statgraphics®

4.3 RESULTS AND DISCUSSION

4.3.1 PLANT WATER STATUS

4.3.1.1 Grapevine and soil water relationships

As the soil dried out, *i.e.* the soil water matric potential (Ψ_M) became more negative, Ψ_S decreased (Fig. 4.1). The lowest Ψ_S, *i.e.* approximately -1.8 MPa, corresponded with a Ψ_M value of *ca.* -0.25 MPa. A linear relationship also occurred between Ψ_L and Ψ_M, but was less significant compared to the one between Ψ_S and Ψ_M (data not shown). Stem water potential has been considered to be less variable than Ψ_L because Ψ_S is less susceptible to fluctuations in the environmental conditions than Ψ_L (Choné *et al.*, 2000). Similar relationships were reported for Cabernet Sauvignon in the Lower Olifants river region (Bruwer, 2010). These relationships confirmed that grapevine water status largely depends on the soil water content, but that variation in atmospheric conditions between the days on which the measurements were carried out probably caused some of the variability in Ψ_L and Ψ_S. However, when the diurnal cycle was followed on the 28 January 2009, the relationships between grapevine water potentials (Ψ_{PD}, Ψ_L, & Ψ_S) and Ψ_M were exceptionally good on a single day basis (Fig.

4.2). When considered over a longer period, climatic conditions will also influence grapevine water potentials.

Both mid day Ψ_L and Ψ_S correlated reasonably well with Ψ_{PD} when the diurnal cycles were measured in January 2009 (Fig. 4.3). Previous findings also showed that Ψ_L and Ψ_S were linearly related to Ψ_{PD} (Williams & Araujo, 2002). Based on the Ψ_{PD} thresholds for different water stress classifications previously proposed (Ojeda *et al.*, 2002; Deloire *et al.*, 2004), the equations in Figure 4.3 were used to estimate corresponding water constraint thresholds for Ψ_L and Ψ_S in grapevines under the given conditions (Table 4.4). The estimated Ψ_L thresholds tended to be lower compared to previously proposed values (Greenspan, 2005). However, it must be noted that the estimated Ψ_L and Ψ_S thresholds would probably not be universally applicable, but merely served as a means to interpret results of the present study in relation to previous water potential classifications.

4.3.1.2 Diurnal leaf water potential changes

On the 28 January 2009, Ψ_L followed the typical diurnal pattern similar to previous findings (Myburgh & Howell, 2006). Maximum Ψ_L occurred at predawn, decreased rapidly during the morning and then steadily increased again during the late afternoon and night (Fig. 4.4 & Fig 4.5). As expected, Ψ_{PD} was substantially lower in the non-irrigated grapevines. The constraint levels increased from none at Ψ_{PD} for all three treatment plots to severe, strong and moderate at 16:00 for non-irrigated, single line and double drip lines, respectively. At Philadelphia, the constraint levels increased to moderate, mild and mild in the non-irrigated, single line and double drip lines grapevines, respectively, with a lowest Ψ_L of -1.7 MPa at 14:00 (Fig 4.5). The differences in atmospheric conditions between the localities seemed to be reflected in the diurnal Ψ_L. At Wellington, the irrigation had a prominent influence on relieving grapevine water constraints. Although the irrigated grapevines at Philadelphia experienced less water constraints than the non-irrigated ones, the influence of irrigation was still evident. Grapevines irrigated by means of the double drip lines, *i.e.* they received double the amount of water, experienced the lowest level of water constraint, for both localities.

The physiological consequences of water constraints depend on the duration of the period that the grapevine is subjected to this constraint. In this study, the differences in the water constraints experienced by grapevines at the two localities were caused by soil water and climate differences. At Wellington, the constraint period and the plant recovery was slow in comparison to Philadelphia, where the plant recovery was more rapid (Fig 4.6 & Fig. 4.7). This recovery rate was influenced by the climate. In the case of grapevines growing at Wellington, which is hot, the constraint was induced earlier at approximately 09:00 and remained at a high level throughout the day. Furthermore, grapevines growing at Wellington experienced the most water constraints at 16:00, whereas at Philadelphia, grapevines were already experiencing less water constraints by 16:00 than at 14:00. Water constraints were only alleviated at 24:00 at Wellington (Fig 4.6). As for Philadelphia, there were no more water constraints by 20:00 (Fig. 4.7). The minimal duration of constraint can be ascribed to the cooler climate. In addition, the soil water status was not dramatically influenced by irrigation treatments at Philadelphia as discussed in Chapter 3. These results illustrated the influence of climate and the importance of the proximity of Philadelphia to the sea which created a cooler environment that cannot as easily be modified by irrigation as at the warmer locality.

The Ψ_L in the non-irrigated grapevines at the two localities (Fig 4.6) shows a significant difference between the localities. This difference can only be explained by the warmer locality having a higher evapotranspiration and lower soil water availability compared to the cooler area, which resulted in more constraints and slower recovery. Although there were little differences between the two localities when grapevines were irrigated by means of single drip lines, differences were still statistically significant (Fig. 4.7). This shows that the extreme constraint level of a plant can be regulated by the water application, with only a minimal climatic effect. In the case of the double drip line grapevines there were almost no differences in diurnal Ψ_L between the two localities (Fig 4.8). These trends showed that water constraints were controlled by the application of water, and masked the climatic influence. The climate was the driving factor behind water constraints in the non-irrigated grapevines, but soil water was the driving force within a locality. However, low level of water constraints could cause excessive vigour and dilution of the berry metabolites (Deloire *et al.,* 2004). In contrast, high levels of grapevine water constraints could inhibit vegetative growth and reduce or inhibit berry growth, photosynthesis and berry maturation (Deloire *et al.,* 2005).

4.3.1.3 Leaf and stem water potential during berry ripening

The mid day Ψ_L and Ψ_S varied considerably between the two localities (Table 4.5 & Table 4.6). The irrigation treatments had a more pronounced impact on grapevine water status at Wellington than at Philadelphia. The largest influence on the plant water status occurred in the non-irrigated grapevines at both localities. Furthermore, grapevines at Wellington irrigated by means of single drip lines also experienced more water constraints than double drip line ones. The lowest level of water constraint measured in terms of Ψ_L was -1.69 MPa and -1.51 MPa at Wellington and Philadelphia, respectively, during berry ripening in 2007/08. In the 2008/09 season, the lowest Ψ_L was -1.90 MPa and -1.82 MPa at Wellington and Philadelphia, respectively. Similar low values were reported for Cabernet Sauvignon during berry ripening in the Lower Olifants River Valley (Bruwer, 2010). In a study on Cabernet Sauvignon in the Napa Valley, the highest water constraints also occurred during véraison (Williams & Araujo, 2002). In 2007/08, the highest means obtained for Ψ_L and Ψ_S were -1.20 MPa and -0.58 MPa, respectively. In the 2008/09 season Ψ_L and Ψ_S were -1.24 MPa and -0.75 MPa, respectively. In 2008/09, grapevines were probably experiencing more constraints due to the very hot conditions in the ripening period compared to 2007/08 as discussed in Chapter 3.

Based on the Ψ_L and Ψ_S water constraint classification (Table 4.4), grapevines growing under non-irrigated conditions experienced strong water deficits at Wellington during 2007/08 (Table 4.5). Grapevines irrigated by means of single drip lines experienced moderate constraints, whilst those irrigated by means of double drip lines experienced mild constraints. In 2008/09, the water constraint levels were higher, *i.e.* moderate and mild for non-irrigated, single drip and double drip, respectively, at Wellington (Table 4.6). At Philadelphia, grapevines of all the treatments experienced moderate water constraints in the 2007/08 season. However, in 2008/09 water constraints were only moderate in non-irrigated grapevines, whereas single and double drip line irrigation induced mild constraints.

It was clear from the Ψ_M and mid day Ψ_L and Ψ_S values that grapevines experienced more water constraints at in the hotter 2008/09 season. The climate influenced the amount of water constraints grapevines experienced when no water was applied, but when irrigation was applied, the effect of the climate was negated. In Wellington, which is the warmer area, there was a more pronounced response to the water applications, and these water applications reduced the water constraint from severe/strong to moderate to mild. In contrast, at the cooler locality near Philadelphia, there was no difference in constraints experienced with the application of water. The lack of constraint development in the cooler area could be as a result of the humidity as well as temperature not being high enough to induce constraints on grapevine functioning. The sum of temperature was less than that of the warmer area. These results indicated that differences in grapevine water status between the two localities depended on the variation in atmospheric conditions between the seasons, proving that there is a climate effect related to water constraints experienced by the grapevine. The importance of Philadelphia's proximity to the Atlantic Ocean can once again be emphasised as the main factor causing and regulating the cool environment at Philadelphia which influenced the soil and plant water status.

4.3.2 VEGETATIVE GROWTH

4.3.2.1 Canopy characteristics

Grapevine canopies showed visual water constraint symptoms at both localities. The non-irrigated grapevines at Wellington visually experienced a high level of water constraints, *i.e.* yellowing of the basal leaves in the bunch zone before véraison, and light green leaves in the canopy (Fig. 4.9). Non-irrigated grapevines that had been subjected to severe water deficits showed premature leaf senescence before véraison (Lopes *et al.,* 2001). The non-irrigated grapevines at Wellington responded in a similar manner. On the other hand, non-irrigated grapevines at Philadelphia showed no visual signs of water constraints (Fig. 4.10). This could be indicative of an ideal situation for grapevine growth. In the moderate climate at Philadelphia, non-irrigated grapevines produced a fuller canopy, *i.e.* no leaf senescence occurred, compared to the hotter climate at Wellington. The different grapevine responses to no irrigation between the two localities indicated that the climate played a role in regulating the vegetative and reproductive growth of the grapevine. However, in addition to climate, soil water matric potential differences could have induced growth differences between the two localities. At Wellington the soil was drier, *i.e.* Ψ_M ranged between -0.20 MPa to -0.34 MPa from December to March (Fig. 3.13), whereas Ψ_M only ranged from -0.10 MPa to -0.16 MPa at Philadelphia (Fig. 3.14).

The single line drip irrigated grapevines did not show any visual water constraint symptoms at any of the two localities (Fig. 4.11 & Fig. 4.12). The mean soil water matric potential ranged from -0.05 MPa to -0.10 MPa at Wellington (Fig. 3.13), and from -0.10 MPa to -0.14 MPa at Philadelphia (Fig. 3.14). Grapevines at both sites were classified as having experienced moderate water constraints as discussed above. However, at Wellington the leaves were light green and the canopy was evenly distributed (Fig. 4.11), whereas grapevines at Philadelphia had darker green leaves and the canopy appeared to be more dense (Fig. 4.12). The fact that water constraints were slightly higher in the single line irrigated grapevines in the warmer climate indicated towards an ideal balance in vegetative and reproductive growth. In contrast, visual observation revealed that unwanted active shoot growth still occurred prior to harvest at the cooler locality.

No visual water constraints symptoms were visible in grapevines of the double line drip treatment. At both localities, *i.e.* irrespective of the climate, the grapevines exhibited rather excessive foliar growth (Fig 4.13 & Fig. 4.14). Cabernet Sauvignon is known to be a vigorous, low yielding grapevine cultivar (De Villiers, 1986), and is therefore more sensitive to excessive water applications (Bruwer, 2010). The mean soil water matric potential of double line drip treatments ranged from -0.02 MPa to -0.08 MPa at Wellington (Fig. 3.13) and from -0.05 MPa to -0.08 MPa at Philadelphia (Fig. 3.14) from December to March (Fig. 3.13 & Fig. 3.14). Due to the high levels of readily available water throughout the season, grapevines only experienced mild water constraints. Under the prevailing conditions, active shoot growth of double drip line irrigated grapevines occurred until harvest. This active vegetative growth during berry ripening could be undesirable as it can become a strong sink which competes with the reproductive growth (Smart & Robinson, 1991). In addition to the phenological stage during which water deficits occur, the intensity as well as the duration of the water constraint that can also contribute to the physiological response of the grapevine (A. Deloire, personal communication). Typical characteristics of high vigour vineyards are grapevines with longer shoots, larger leaves and more lateral shoots than grapevines in lower vigour vineyards (Smart *et al*., 1985). The causes of poor uniformity in vineyards can be due to soil type variation, irrigation, disease, irregular pruning and varied grapevine age (Long, 1987).

The spurs per grapevine and per meter cordon were similar for both seasons and at both localities (Table 4.7). Likewise, the shoots per meter cordon did not vary. However, in the 2007/08 season, there were more shoots per grapevine at Wellington than in 2008/09. Irrigation treatments only had an effect on shoot numbers at Wellington in 2007/08. The shoot length and leaf area responses to the water and seasonal temperature differences showed that vegetative growth increased with the increase in water applied and subsequent decrease in water constraints (Table 4.8). The vegetative growth appeared to be sensitive to climate, confirming that grapevine physiological functioning is temperature sensitive. At Wellington, vegetative growth tended to be slightly less in the very hot 2008/09 season compared to the hot 2008/07 season (Table 3.6). Since Philadelphia had a moderate climate due to the proximity of the ocean, the canopy did not respond to the irrigation treatments compared to the situation at Wellington.

Main shoot lengths tended to be longer at Wellington in the 2007/08 season, and length tended to increase with an increase in irrigation (Table 4.8). Weak Cabernet shoots, *i.e.* shorter than 30 cm, produced berries with lower sugar, less colour and lower phenol concentrations, whereas 1.2 m shoots were regarded to be the norm for producing optimal quality for Cabernet Sauvignon (Long, 1987). Since the shoot lengths of the irrigated grapevines were 1.6 m and longer, irrigation seemed to have resulted in excessive vegetative growth and less homogenous shoots. In the hotter 2008/09 season, there was less variation in shoot length and the average shoot length at Wellington was closer to the desired length, ranging between 1.0 m and 1.3 m. In addition to influencing available water in the soil, the warmer conditions could have limited temperature dependent physiological functions. In the 2007/08 season, the non-irrigated grapevines showed little water constraints, as well as excessively strong growth compared to the irrigated ones. Similar to the situation at Wellington, shoots were close to the desired length at Philadelphia. Lateral shoot growth occurred during both seasons, irrespective of locality or irrigation system (Table 4.8). However, secondary shoot growth off the lateral shoots only occurred during the 2007/08 season. This indicated that the grapevines were essentially functioning more actively in the 2007/08 season than during the 2008/09 season.

As the soil became drier, the leaf area per meter cordon decreased at both localities (Table 4.9), with the exception of 2007/08 at Philadelphia. At Wellington, the total leaf area per meter cordon was 50% lower in the 2008/09 season compared to the 2007/08 season. The leaf area index of the grapevines followed a similar trend in both seasons (Fig. 4.15). An effect on berry ripening is obtained when the main shoot leaf surface to lateral shoot leaf surface ratio is approximately 0.7 (Hunter, 2000). The primary to secondary leaf area ratio indicated that there was generally more secondary growth at Philadelphia than at Wellington, irrespective of the season (Fig. 4.16). These results illustrated that the warmer temperatures could negatively influence vegetative growth of grapevines (Table 4.9). In contrast, there were almost no seasonal differences in total leaf area at Philadelphia where the climate classified as moderate in both seasons. The higher temperatures at Wellington could have been too extreme for the optimal grapevine functioning. During 2008/09, there were hardly any differences between treatments. This can be a result of the high temperatures interacting with plant water use, causing the grapevines to experience severe water constraints (*i.e.* Ψ_L < -0.2 MPa) in the second season. This probably resulted in the inhibition or slowing down of plant functioning. Grapevine leaf area showed a two-fold increase from low to high vigour experimental plots, but the leaf area to fruit mass ratio was not affected (Smart *et al*., 1985).

Grapevine growth at Philadelphia tended to be more vigorous as available water was sufficient and the moderate climate was not hot enough to interact with the water to induce constraints. This indicated that conditions at Philadelphia were favourable for optimal growth, even for the non-irrigated grapevines. The addition of more water would create a luxurious environment for vigorous growth as the grapevines were already established. Since the canopies of grapevines irrigated by single and double line drip were so vigorous, the wine quality characteristics could possibly be negatively influenced. On the other hand, Wellington required water for the optimal vegetative functioning of the grapevine.

The analysis of the leaf blades in the 2008/09 season showed that element contents were within the norms for grapevines (Table 4.10), which indicated that the grapevines were healthy and functioning well. The lack of differences in the leaf element contents between the non-irrigated and irrigated grapevines confirmed that differences in grapevine response were primarily due to water and seasonal temperature variations.

4.3.2.2 Cane characteristics

Similar to canopy characteristics, the cane characteristics at pruning varied between the two localities (Table 4.11). Grapevines growing at Wellington had a higher pruning mass compared to the ones Philadelphia. The leaf area per meter cordon was higher in the 2007/08 season than in the 2008/09 season at Wellington as it was a ‘very hot’ season, whereas the cane mass at pruning was higher in the 2008/09 season than the 2007/08 season. As the resources in the canes were not all being used in the canopy or in shoot growth, canes were probably thicker. Active growth in the post véraison period could contribute positively to the high pruning mass in the 2008/09 season. It should also be noted that canopy management practices such as tipping and topping, throughout the season was done at Philadelphia, but less frequently at Wellington. This could have contributed to the pruning mass differences observed at the two localities.

The cane mass of grapevines increased with the decrease in constraints due to irrigation (Table 4.11). Conradie *et al.* (2002) also showed that cane mass of grapevines in a wetter soil were significantly higher than that of grapevines in a drier soil type in the same vineyard. A reduction in shoot growth is one of the first visible symptoms of grapevine water constraints (Williams, 2000). An increase in irrigation increased the vegetative growth of the grapevine, resulting in more leaves in the canopy. Even with an increase in shoot length, the cane mass was still low in the high vigour situations due to thinner shoot and more leaves. According to Archer (2001), the quality of a grape bunch can be directly related to the physiological quality of the shoot bearing it, *i.e.* homogenous quality grapes produced on homogenous shoots produced the best quality grapes and will have best potential for top quality wines. At Wellington, the double drip line irrigated grapevines produced the highest cane mass at pruning, as well as the longest shoots. The same trend occurred at Philadelphia.

4.3.3 YIELD AND ITS COMPONENTS

Berry mass variation between treatment plots indicated that berry size was water related during both seasons (Table 4.12). The smallest berries were produced under high temperature and non-irrigated conditions at Wellington. These grapevines had a mean Ψ_L and Ψ_S of -1.81 MPa and -1.74 MPa, respectively. The largest berry mass was obtained where grapevines were irrigated by means of double drip lines. At Philadelphia, irrigation only tended to increase berry size in the second season, berries were 40% bigger for the PDD treatment. Therefore, irrespective of the climate, more water caused berry size to increase. Under the given conditions irrigation produced berries that were comparable to *ca.* 1.3 g per berry for Cabernet Sauvignon as determined over a ten year period in Stellenbosch, Robertson and Lutzville (Archer & Hunter, 2000).

The higher the water constraints which were induced by the lower soil matric potential during the critical period from flowering to harvest, the greater the reduction in berry size compared to grapevines subjected to less water constraints. At the beginning of berry development, the green active berries are sensitive to water availability (Van der Westhuizen, 1972; Williams, 2000). If water is limited for approximately 40 days after fruit set, the berry size development will be limited and berries cannot be enlarged by further water applications. Pre véraison water deficits can reduce berry size (Van Leeuwen *et al*., 2004). In the warmer inland regions of South Africa, water constraints during the early stages of berry development also reduced berry size (Myburgh, 2006). Water constraints applied from flowering to véraison irreversibly modified the size of Shiraz berries, even when followed by normal water applications from véraison to harvest (Ojeda *et al.,* 2001).

Both at Wellington and Philadelphia, irrigation tended to increase the number of berries per bunch in both seasons (Table 4.12). Bunches at Philadelphia were substantially bigger than those at Wellington in both seasons (Table 4.12). At Wellington, bunches tended to be smaller in the 2008/09 season than the 2007/08 season, probably due to temperature effects on grapevine functioning (Table 3.4). Furthermore, the effects of irrigation on berry size and numbers per bunch reflected in the bunch mass at Wellington during both seasons. However, in the case of Philadelphia, irrigation had no effect on bunch mass in 2007/08, and only tended to increase bunch mass in 2008/09 season.

Bunch numbers tended to be considerably lower at Philadelphia compared to Wellington (Table 4.12). Since wind speeds above 4 m/s will induce stomatal closure in the grapevine leaves (Greenspan, 2008) and reduce the grapevine transpiration (Campbell-Clause, 1998), high wind speeds that occurred at Philadelphia from November to February (Table 3.4) could have reduced transpiration and grapevine functioning compared to Wellington. This constraint could have contributed to a reduction in flowering percentage and fruit set (Greenspan, 2008).

Yield of grapevines growing at Philadelphia tended to be lower than those at Wellington (Table 4.12). Irrigation had a more pronounced influence on the yield at Wellington than at Philadelphia. The yield of potted grapevines also increased with irrigation compared to permanently dry soil conditions (Rühl and Alleweldt, 1985). At Wellington, irrigation seemed to have balanced vegetative and reproductive growth, thereby producing the highest yield. From these results, it is clear that the application of water is required for the optimal functioning of the grapevine in hot areas to ensure exposure to moderate constraints throughout the season. The total yield at Philadelphia was not influenced by application of water. Due to the moderate climate at Philadelphia, which moderated water constraints, grapevines were apparently not influenced by irrigation. This indicated that the environment could be an important factor for the efficiency of irrigation. The climate could be the dominating factor in grapevine response since the application of water only caused a response in the hotter climate by inducing more constraints. Yield and its components showed the same trend relating to temperature and water application (Table 4.12). Yield increased with a decrease in grapevine constraints and decreased with an increase in temperature as seen under the non-irrigated conditions. However, water can be used to manipulate the plant constraints in a specific environment.

Harvest mass to cane mass ratio is a good indicator of the balance between vegetative growth and yield and has been used in South Africa for a number of years. Values less than 5 is linked to excessive vegetative growth and values greater than 12 indicate over production for specific vigour (Hunter, 2000). The yield to pruning mass at Wellington decreased with increased irrigation volume, whereas yield to pruning mass at Philadelphia increased with the application of water, due to the climatic difference between the two localities (Fig 4.17). Since the yield and pruning mass was balanced, it indicated that single line irrigated grapevines at Wellington were functioning optimally in its environment.

4.4 CONCLUSIONS

Results indicated that mid day Ψ_S was a more sensitive indicator of grapevine water constraints compared to Ψ_L. Variation in Ψ_S was linearly related to Ψ_M. The relationship between different grapevine water potential parameters could be used to determine water constraint thresholds in terms of Ψ_S and Ψ_L. In the hotter 2008/09 season water constraints, as reflected in Ψ_M, Ψ_{PD}, Ψ_L and Ψ_S, were more pronounced than in 2007/08, particularly in the non-irrigated grapevines. At Wellington water constraints were moderate and mild for the non-irrigated and irrigated grapevines, respectively. In the moderate climate at Philadelphia only mild constraints occurred, irrespective of water application. Grapevines at Philadelphia, closest to the ocean tended to experience less water constraints over the course of the day compared to the ones at Wellington. This effect became more pronounced as the season progressed, not only due to the changes the atmospheric conditions, but also as a result of drier soil. Single line irrigation increased water constraints in the grapevines compared to the ones that received more water by means of the double line system. The effect of the warmer climate on water constraints could be modified by the application of water, but in the cooler climate where low evapotranspiration occurred, it could not be controlled by the application of water. This showed that the grapevine water status was directly dependent on soil water status. Furthermore, it emphasised the importance of the soil water holding capacity, and thereby the ability to minimize critical grapevine water constraints. In addition to the phenological stage during which water constraints occur, the intensity and duration of water status constraints are critical for the physiological response of the grapevine. Climate appeared to be the driving factor for water constraints at Philadelphia, whereas the soil water content played a more prominent role at Wellington.

The general vegetative growth response to irrigation and seasonal temperature differences showed that shoot length, leaf area and cane mass increased with the increase of water availability. The secondary growth of grapevines at Philadelphia was higher compared to the ones at Wellington. At the warmer locality, canopy was yellow and sparse because of the senescence of leaves. In contrast, grapevines growing in the cooler climate had shorter shoots, bright green leaves and a fuller canopy. Therefore, it is essential to irrigate in warm climates such as Wellington, but it might be not necessary in cooler climates such as Philadelphia. Moderate water constraints could balance vegetative and reproductive growth, and limit shoots to the desired length of *ca.* 1.2 m recommended for producing and ripening optimal quality Cabernet Sauvignon grapes.

The moderate constraints experienced by the non-irrigated grapevines at Philadelphia resulted in less bunches per grapevine, but there were more berries per bunch than at Wellington. However, in spite of the 60% less berries per bunch, single drip line irrigated grapevines at Wellington produced the highest yield. Bunch and berry mass increased with an increased application of water. The smallest berries were obtained at Wellington where grapevines grew under non-irrigated conditions. The largest berries where produced at Philadelphia where grapevines were irrigated by means of double drip lines. Therefore, irrigation and lower temperatures increased berry size, whilst a lack of water and warmer temperatures which limited optimal grapevine functioning, decreased berry size. Consequently, yield increased with a decrease in grapevine water constraints induced by the application of water.

Measurement of diurnal leaf water potential cycles is required to understand the effect of climate and soil on the grapevine water status. Warmer sites have a higher evaporation and transpiration demand compared to cooler climates, therefore placing a greater demand on the soil. Grapevines in the warmer climate required the application of water to alleviate severe constraints, as they seem to function optimally under moderate constraints. Optimal grapevine functioning means the vegetative and reproductive growth of the grapevine is balanced. This was evident in the moderate constraint conditions, namely single drip line at Wellington and non-irrigated at Philadelphia. Therefore, the climate is an important consideration in irrigation scheduling. Irrigation would probably only cause grapevine responses if the water constraints are higher than moderate in a hot climate.

4.5 LITERATURE CITED

Améglio, T., Archer, P., Cohen, M., Valancogne, C., Daudet, F.-A., Dayau, S. and Cruiziat, P. (1999). Significance and limits in the use of predawn leaf water potential for three irrigation. *Plant and Soil*, **207**, 155-167

Archer, E. (2001). Die Verband tussen stokvormings-praktyke en druifgehalte. *Wynboer Tegnie.* **145**, 19-20.

Archer, E. & Hunter, J.J. (2000). Increased yield in wine grapes for specific production goals. http://www.wynboer.co.za/recentarticles/1003yield.php3 Date of access: 20 October 2009.

Bergqvist, J., Dokoozlian, N. & Ebisuda, N. (2001). Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in Central San Joaquin Valley of Claifornia. *Am. J. Enol. Vitic*. **52**,1-7.

Bogart, K. (2006). Persistence of vegetal characters in wine grapes and wine. *Practical Vinetard & Winery*, March/April 2006, **86**,13-20.

Bruwer, R.J. (2010). The edaphic and climatic effects on production and wine quality of Cabernet Sauvignon in the lower Olifants River Region. M.Sc. Agric Thesis. Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Buttrose, M., Hale, C. & Kliewer, W. (1971). Effect of temperature on the composition of Cabernet Sauvignon berries. *Am. J. Enol. Vitic.* **22**,71-75.

Campbell-Clause, J.M. (1998). Stomatal response of grapevines to wind. *Austr. J. Exp. Agric.* **38**, 77-82.

Carbonneau, A. (1998). Aspects qualitatifs, 258-276. In Proc. XXVIIth World Congress of Vine and Wine. Bratislava. Traité d'irrigation, Tiercelin J.R., Lavoisier Tec et Doc ed., p. 1011.

Choné, X., Van Leeuwen, C., Chery, P. & Ribèreau-Gayon, P. (2001). Terrior influence on water status of non-irrigated Cabernet Sauvignon (Vitis vinifera). Vegetative development, must and wine composition (Example of Medoc top Estate Vineyards, Saint Julien area, Bordeaux, 1997). *S.Afri. J. Enol. Viti.* **22**, 1.

Conradie, W.J., Carey, V.A., Bonnardot, V., Saayman, D., & Van Schoor, LH. (2002). Effect of different environmental factors on the performance of Sauvignon blanc grapes in Stellenbosch/Durbanville districts of South Africa. I. Geology, soil climate, phenology, and grape composition. *S.Afri. J. Enol. Viti.*, **23**, 78-91.

Deloire, A., Carbonneau, A., Wang, Z. & Ojeda, H. (2004). Vine and water. *J. Int. Sci. Vigne Vin.* **38**, 1-13.

Deloire, A., Vaudour, E., Carey, V., Bonnardot, V. & Van Leeuwen, C. (2005). Grapevine responses to terroir: A global approach. *J. Int. Sci. Vigne Vin.* **39**, 149-162.

De Villiers, F.S. (1986). Wine grape cultivars: Cabernet Sauvignon. VORI 159/1986. Farming in South Africa.

Greenspan, M. (2005). Integrated irrigation of California winegrapes. *Practical Vineyard & Winery*, March/April 2005, **79**, 21-43.

Greenspan, M. (2008). Row direction - Which end is up? Wine Business Monthly, July 2008, http://www.winebusiness.com/wbm/?go=getArticle&dataId=58458 Date of access: 19 November 2009.

Hunter J.J. (2000). Implications of seasonal canopy management and growth compensation in grapevine. *S. Afr. J. Enol.Vitic.* **21**, 81-91.

Lopes, C., Vicente-Paulo, J., Santos, T., Rodrigues, M.L., Barroso, J. & Chaves, M.M. (2001). An attempt to quantify grapevine water constraint in a mediterranean environment. In: Proc. 12th GESCO Conference, 3-7 July 2001, Montpellier, France, 43-48.

Long, Z.R. (1987). Manipulation of grape flavour in the vineyard: California, North Coast region. In: Lee, T.H. (ed). Proc. 6th Austr. Wine Ind. Conf., Adelaide. Pp 82-88.

Ojeda, H., Andary, C., Kraeva, E., Carbonneau, A. & Deloire, A. (2002). Influence of pre- and post véraison water deficits on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. *Am. J. Enol. Vitic.* **53**, 261-267.

Ojeda, H., Deloire, A. & Carbonneau, A. (2001). Influence of water deficits on grape berry growth. *Vitis* **49**, 141-145.

McCarthy, M.G. & Coombe, B.G. (1985). Water status and wine grape quality. *Acta Hortic.* **171**, 447-456.

McCarthy, M.G., Cirami, R.M. & McCloud, P. (1983). Vine and fruit response to supplementary irrigation and canopy management. *S. Afr. J. Enol.Vitic*. **4**, 2.

Myburgh, P.A. (1998). Water consumption of South African vineyards: A modeling approach based on the quantified combined effects of selected viticultural, soil and meteorological parameters. PhD. Dissertation, University of Stellenbosch, Private Bag X1, Matieland, 7602, South Africa.

Myburgh, P. (2006). Irrigation management with particular reference to wine quality - a brief overview of South African research. *Wynboer Technical Yearbook* 2006, 50-53.

Myburgh, P.A. & Howell, C.L. (2006). Water relations of *Vitis vinifera* L. cv. Sunred Seedless in response to soil water depletion before harvest. *S. Afr. J. Enol. Vitic.* **27**, 196-200.

Pellegrino, A., Lebon, E., Voltz, M. & Wery, J. (2004). Relationship between plant and soil water status in vine (Vitis vinifera L.). *Plant and Soil.* **266**, 129-142.

Rühl, E. & Alleweldt, G. (1985). Investigations into the influence of time of irrigation on yield and quality of grapevines. *Acta Hort.* **171**, 457-462.

Saayman, D. (1992). Natural influences and wine quality. Part 2: The role of soil. *Wynboer*, August 1992, 49-51.

Scholander, P.F., Hammel, H.J., Bradstreet, A, and Hemmingse, E.A. (1965). Sap pressure in vascular plants. *Science.* **148**, 339-346.

Schultz H.R., Matthews, M.A. (1993). Xylem development and hydraulic conductance in sun and shade shoots of grapevine (*Vitis vinifera* L.), evidence that low light uncouples water transport capacity from leaf area. *Planta* **190**:393-406.

Smart, R. (1985). Principles of grapevine canopy microclimate manipulations with implications for yield and quality. A review. *Am.J. Enol. Vitic.* **36**, 230-239.

Smart, R. & Robinson, M. (1991). Sunlight into wine. *Handbook for winegrape canopy management. Winetitles, Australia.*

Van der Westhuizen, J.H. (1972). Waterbehoeftes van die wingerdstok. *Wynboer*, November 1972, 20B.

Van Leeuwen, C., Friant, Ph., Soyer,J.-P., Molot, C., Chone, X. & Dubourdieu, D. (2000). L'interet du dosage de l'azote total et l'azote assimilable dans le mout comme indicateur de la nutrition azotee de la vigne. *J. Int. Sci. Vigne Vin.* **34**, 75-82.

Van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S. & Dubourdieu, D. (2004). Influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic*. **55**, 207-217.

Van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D. and Gaudillere, J.-P. (2009). Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? *J. Int. Sci. Vigne Vin*. **43**, 121-134.

Van Zyl, J.L. (1981). Waterbehoefte en besproeiing. In: Burger, J. & Deist, J. (eds.) Wingerdbou in Suid-Afrika. CTP Boekdrukkers, Cape Town, p. 237-238.

Van Zyl, J.L. (1986). Canopy Temperature as a water constraint indicator in vines. *S. Afr. J. Enol. Vitic.* **7**, 2.

Williams, L.E. (2000). Grapevine Water Relations In: Raisin Production Manual. University of California, Agriculture & Natural Resources Publication 3393, Oakland, CA, p. 121-126.

Williams, L.E. & Araujo, F.J. (2002). Correlations among predawn leaf, midday leaf, and midday stem water potential and their correlations with other measures of soil and plant water status in *Vitis vinifera. J. Amer. Soc. Hort. Sci.* **127**, 448-454.

Winkel, T. & Rambal, S. (1993). Influence of water constraint on grapevines growing in the field: from leaf to whole plant response. *Aust. J. Plant Physiol*. **20**, 143 – 57.

Table 4.1. Thresholds for predawn leaf water potential (Ψ_{PD}**)** and level of water constraints in grapevines as proposed by Carbonneau (1998).

Class	Ψ_{PD} (MPa)	Level of constraint
0	-0.0 MPa >Ψ_{PD}> -0.2 MPa	No water deficit
1	-0.2 MPa >Ψ_{PD}> -0.4 MPa	Mild to moderate water deficit
2	-0.4 MPa >Ψ_{PD}> -0.6 MPa	Moderate to severe water deficit
3	-0.6 MPa >Ψ_{PD}> -0.8 MPa	Severe to high water deficit

Table 4.2. Thresholds for leaf water potential (Ψ_L) and level of water constraints in grapevines as proposed by Greenspan (2005).

Class	Ψ_L (MPa)	Level of constraint
0	-0.0 MPa >Ψ_L> -0.1 MPa	No water deficit
1	-0.1 MPa >Ψ_L> -1.2 MPa	Mild water deficit
2	-1.2 MPa >Ψ_L> -1.4 MPa	Moderate water deficit
3	-1.4 MPa >Ψ_L> -1.6 MPa	High water deficit
4	Ψ_L< -1.6 MPa	Severe water deficit

Table 4.3. Thresholds for stem (Ψ_S), leaf (Ψ_L) and pre-dawn (Ψ_{PD}) water potentials and level of water constraints in grapevines as proposed by Van Leeuwen *et al*., (2009).

Level of constraint	Thresholds (MPa)		
	Ψ_S	Ψ_L	Ψ_{PD}
No water deficit	> -0.6	> -0.9	> -0.2
Weak water deficit	-0.6 to -0.9	-0.9 to -1.1	-0.2 to -0.3
Moderate to weak water deficit	-0.9 to -1.1	-1.1 to -1.3	-0.3 to -0.5
Moderate to severe water deficit	-1.1 to -1.4	-1.3 to -1.4	-0.5 to -0.8
Severe water deficit	< -1.4	< -1.4	< -0.8

Table 4.4. Thresholds calculated to quantify grapevine water constraints in the Swartland region using leaf (Ψ_L) and stem (Ψ_S) water potential in relationship to predawn leaf water potential (Ψ_{PD}).

Level of constraint	Thresholds (MPa)		
	Ψ_{PD}	Ψ_S	Ψ_L
No water deficit	-0.2	-0.6	-1.3
Mild water deficit	-0.4	-0.86	-1.42
Moderate water deficit	-0.6	-1.13	-1.55
Strong water deficit	-0.8	-1.39	-1.67
Severe water deficit	-1.0	-1.65	-1.8

Table 4.5. Mid day leaf (Ψ_L) and stem (Ψ_S) water potential as measured during the ripening period in Cabernet Sauvignon in six experiment plots where soil and grapevine water status was monitored at two localities in the Swartland region during the 2007/08 season.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	Ψ_L (MPa)					
21 January	-1.60e[2]	-1.31b	-1.20a	-1.38bc	-1.45cd	-1.53de
07 February	-1.69b	-1.61ab	-1.59ab	-1.50a	-1.63ab	-1.58ab
19 February	-1.61b	-1.39ab	-1.31a	-1.48b	-1.48b	-1.60b
Mean 2008	-1.63c	-1.44a	-1.37a	-1.46a	-1.52ab	-1.57bc
	Ψ_S (MPa)					
21 January	-1.17d	-0.88b	-0.58a	-0.93bcd	-0.96bc	-1.05cd
07 February	-1.51d	-1.26c	-0.95a	-0.97a	-1.10ab	-1.13bc
19 February	-1.23c	-0.78b	-0.63a	-1.06c	-1.09c	-1.24c
Mean 2008	-1.30d	-0.97b	-0.72a	-0.98b	-1.05c	-1.14c

[1] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.
[2] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$)

Table 4.6. Mid day leaf (Ψ_L) and stem (Ψ_S) water potential as measured during ripening period in Cabernet Sauvignon in six experiment plots where soil and grapevine water status was monitored at two localities in the Swartland region during the 2008/09 season.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	Ψ_L (MPa)					
15 January	-1.69c[2]	-1.53b	-1.33a	-1.55b	-1.30a	-1.22a
28 January	-1.90c	-1.60b	-1.43a	-1.48ab	-1.46ab	-1.38a
10 February	-1.83e	-1.54d	-1.24a	-1.59d	-1.45c	-1.35b
Mean 2009	-1.81d	-1.56c	-1.33a	-1.54c	-1.40b	-1.31a
	Ψ_S (MPa)					
15 January	-1.64d	-1.02b	-0.65a	-1.16c	-0.94b	-0.78a
28 January	-1.82c	-1.27b	-0.85a	-1.25b	-0.90a	-0.79a
10 February	-1.76d	-1.03c	-0.75a	-0.97bc	-1.00c	-0.90b
Mean 2009	-1.74e	-1.10c	-0.75a	-1.13d	-0.95b	-0.82a

[1] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.
[2] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$)

Table 4.7. Spur and shoot number of Cabernet Sauvignon grapevines measured in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	Spurs per meter cordon					
2007/08	6	7	6	6	6	7
2008/09	7	7	6	6	6	7
	Spurs per grapevine					
2007/08	9	10	9	8	8	8
2008/09	10	10	9	8	8	8
	Total shoots per meter cordon					
2007/08	18	22	25	13	14	18
2008/09	16	17	16	16	16	18
	Total shoots per grapevine					
2007/08	27	32	38	16	16	21
2008/09	25	25	23	19	19	21

[1] Refer to Table 3.2 for description of plots. "W" and "P" indicate Wellington and Philadelphia, respectively, whereas "NI", "SD" and "DD" indicate non-irrigated, single line drip and double line drip.

Table 4.8. Vegetative growth components at véraison of Cabernet Sauvignon grapevines measured in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[(1)]	WSD	WDD	PNI	PSD	PDD
	Main shoot length (m)					
2007/08	1.3	1.6	1.7	1.2	1.3	1.6
2008/09	1.0	1.1	1.3	1.1	1.1	1.1
	Main shoot leaf number per shoot					
2007/08	21	23	23	22	23	26
2008/09	16	17	22	17	15	17
	Main shoot leaf area (m^2)					
2007/08	0.2	0.2	0.2	0.2	0.2	0.2
2008/09	0.1	0.2	0.2	0.1	0.1	0.1
	Lateral shoot length (m)					
2007/08	2.9	0.7	0.9	0.4	0.9	1.2
2008/09	0.2	0.5	0.8	0.8	1.0	1.4
	Lateral shoot number					
2007/08	2	4	4	2	4	4
2008/09	2	4	7	4	6	6
	Lateral shoot leaf number					
2007/08	8	21	20	15	21	39
2008/09	24	27	35	34	39	52
	Lateral shoot leaf area (m^2)					
2007/08	0.04	0.10	0.10	0.08	0.14	0.27
2008/09	0.06	0.08	0.10	0.10	0.13	0.19
	Secondary leaf number					
2007/08	12	16	29	8	13	12
2008/09	0	0	0	0	0	0
	Secondary leaf area (m^2)					
2007/08	0.04	0.04	0.10	0.04	0.06	0.04
2008/09	0	0	0	0	0	0
	Total leaf number per shoot					
2007/08	40	60	72	45	57	77
2008/09	40	44	56	51	54	69

[(1)] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 4.9. Total leaf area and fruit to leaf balance at véraison of Cabernet Sauvignon grapevines measured in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	Total leaf area per shoot (m^2)					
2007/08	0.3	0.3	0.4	0.3	0.4	0.6
2008/09	0.2	0.2	0.2	0.2	0.3	0.3
	Total leaf area per meter cordon (m^2)					
2007/08	4.8	7.0	10.9	4.2	5.7	9.7
2008/09	2.6	3.8	4.1	3.5	4.0	5.5
	Total leaf area per grapevine (m^2)					
2007/08	7.2	10.6	16.3	5.0	6.8	11.6
2008/09	3.9	5.6	6.1	4.2	4.8	6.6
	Fruit: leaf balance per m cordon					
2007/08	0.4	0.4	0.3	0.5	0.4	0.3
2008/09	0.6	0.8	0.6	0.6	0.7	0.5

(1) Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 4.10. Leaf element contents of Cabernet Sauvignon grapevines measured in six experiment plots at two localities in the Swartland region during the 2008/09 season.

	Locality					
	Wellington			Philadelphia		
Element	**WNI**[(1)]	**WSD**	**WDD**	**PNI**	**PSD**	**PDD**
N (%)	2.68	2.44	2.57	1.94	2.07	2.14
P (%)	0.41	0.30	0.35	0.43	0.50	0.82
K (%)	0.96	0.80	1.00	0.58	0.70	0.69
Ca (%)	2.42	2.51	2.59	2.82	2.56	2.96
Mg (%)	0.46	0.40	0.36	0.45	0.39	0.44
Na (mg/kg)	286	223	339	566	481	504
Mn (mg/kg)	378	143	180	296	252	241
Fe (mg/kg)	151	136	225	226	199	181
Cu (mg/kg)	9	7	10	9	9	11
Zn (mg/kg)	26	22	31	26	25	27
B (mg/kg)	64	63	66	83	89	95

[(1)] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 4.11. Pruning components of Cabernet Sauvignon grapevines measured in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	Mass per cane (g)					
2007/08	31.9	42.5	51.6	54.2	68.2	72.6
2008/09	54.7	63.5	100.0	34.8	39.5	57.1
	Cane mass per meter cordon (kg)					
2007/08	0.58	0.92	1.31	0.72	0.92	1.27
2008/09	0.90	1.05	1.56	0.56	0.64	1.00
	Cane mass per grapevine (kg)					
2007/08	0.87	1.38	1.96	0.87	1.11	1.53
2008/09	1.34	1.57	2.33	0.67	0.77	1.20
	Cane mass (t/ha)					
2007/08	2.3	3.7	5.2	2.6	3.4	4.6
2008/09	2.5	3.6	4.9	2.8	3.4	4.4

[1] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 4.12. Yield and its components for Cabernet Sauvignon grapevines measured in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
			Mass per berry (g)			
2007/08	1.0	1.3	1.4	1.2	1.2	1.5
2008/09	0.9	1.1	1.2	1.0	1.2	1.4
			Berries per bunch			
2007/08	84	93	96	146	138	130
2008/09	78	91	102	122	141	154
			Bunch mass (kg)			
2007/08	0.08	0.12	0.13	0.18	0.17	0.19
2008/09	0.07	0.10	0.12	0.15	0.17	0.17
			Bunches per grapevine			
2007/08	34	37	35	13	14	15
2008/09	33	44	33	16	18	19
			Bunches per meter cordon			
2007/08	23	24	24	11	12	13
2008/09	22	29	22	14	15	16
			Yield per grapevine (kg)			
2007/08	2.7	4.5	4.7	2.4	2.4	2.9
2008/09	2.4	4.4	3.9	2.5	3.1	3.1
			Yield per meter cordon (kg)			
2007/08	1.8	3.0	3.2	2.0	2.0	2.4
2008/09	1.6	2.9	2.6	2.1	2.6	2.6
			Yield (t/ha)			
2007/08	7.3	12.1	12.6	7.2	7.2	8.9
2008/09	6.4	11.6	10.4	7.5	9.5	9.5

(1) Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

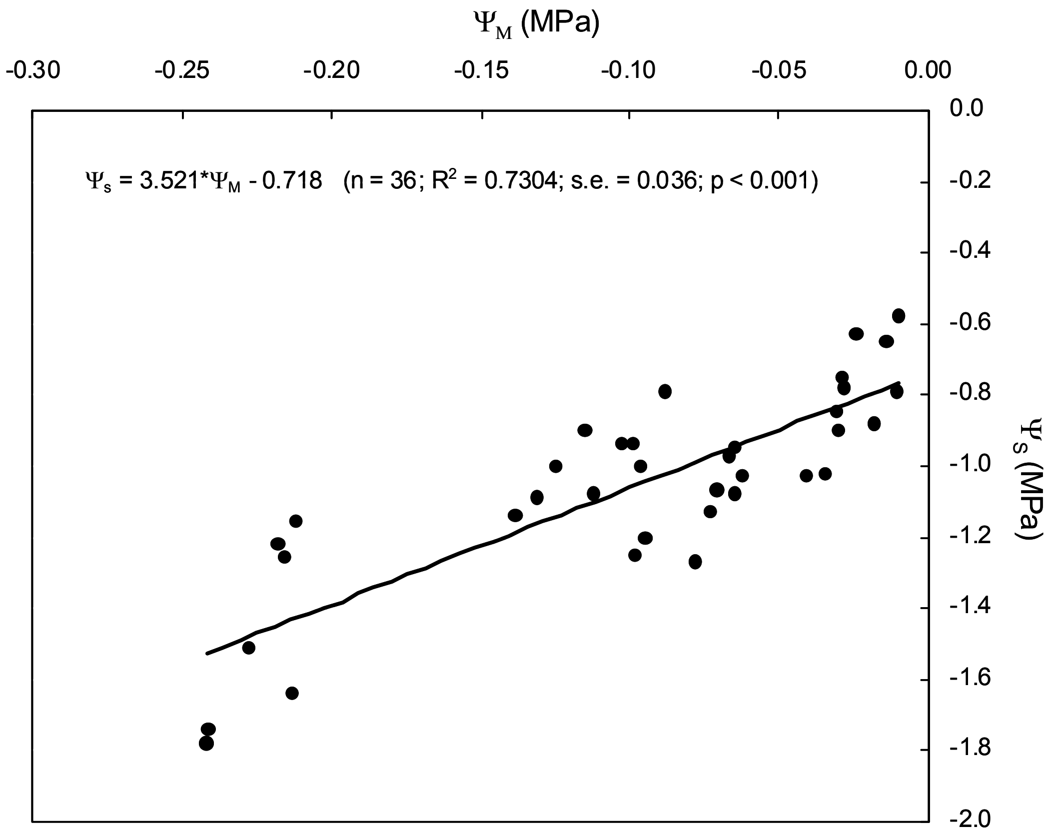

Figure 4.1. Relationship between stem water potential (Ψ_S) in Cabernet Sauvignon grapevines and soil water matric potential (Ψ_M) as measured during the 2007/08 and 2008/09 seasons at Wellington and Philadelphia in the Swartland region.

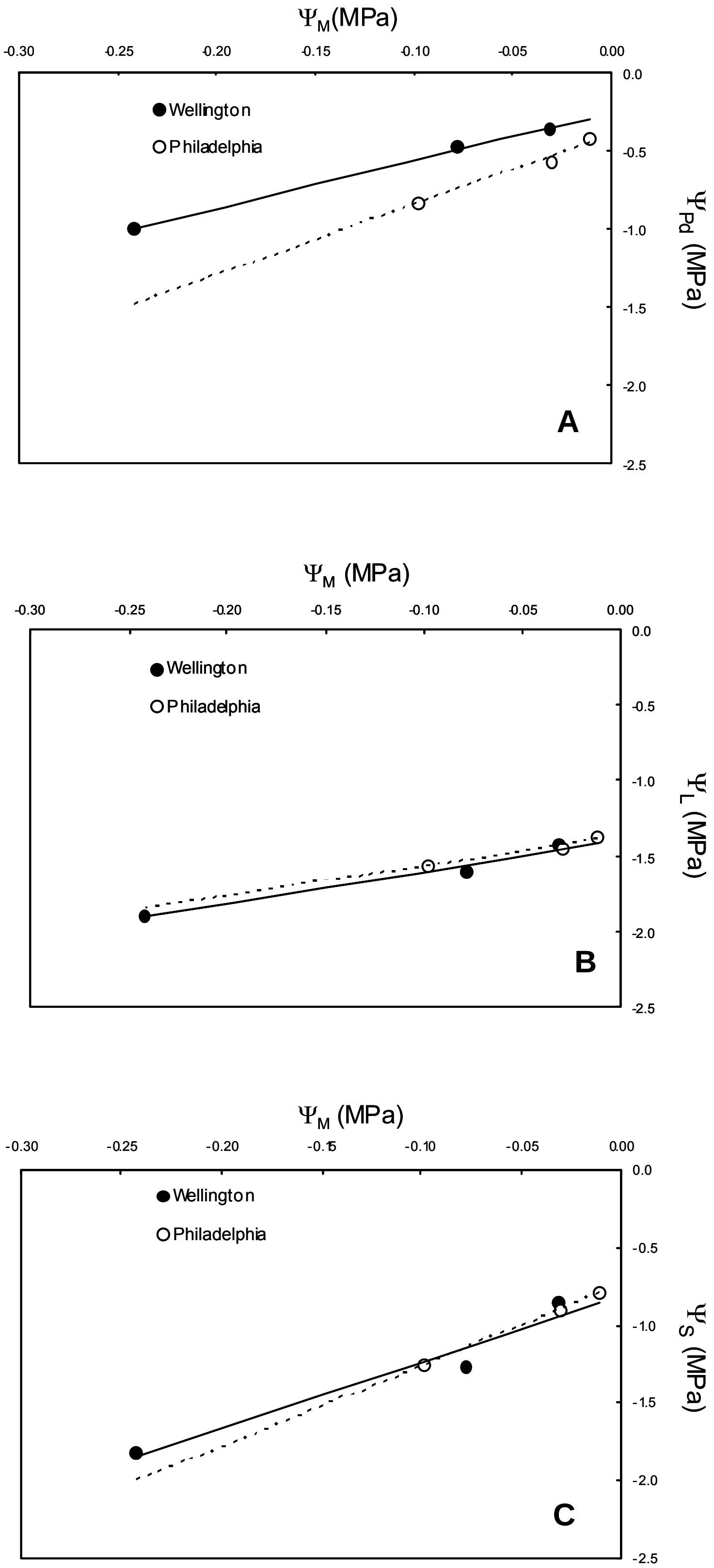

Figure 4.2. Relationship between (A) pre-dawn (Ψ_{PD}), (B) leaf (Ψ_{L}), as well as (C) stem (Ψ_{S}) in Cabernet Sauvignon grapevines and soil water matric potential (Ψ_{M}) as measured on 28 January 2009 near Wellington and Philadelphia.

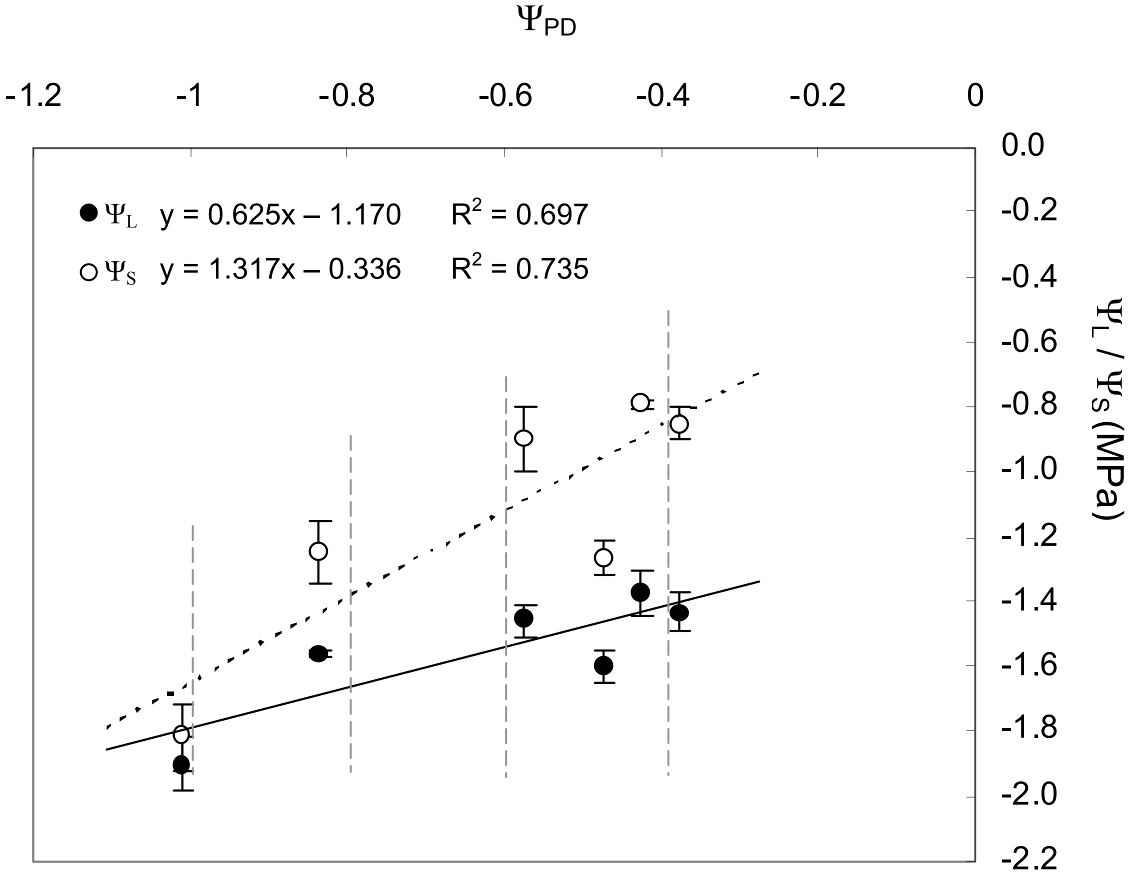

Figure 4.3. The relationship between midday leaf (Ψ_L) and stem (Ψ_S) water potential and predawn leaf water potential (Ψ_{PD}) in Cabernet Sauvignon grapevines. Dashed vertical lines indicate thresholds for grapevine water constraints as proposed by Ojeda *et al*. (2002). Vertical lines indicate standard deviation (n = 3).

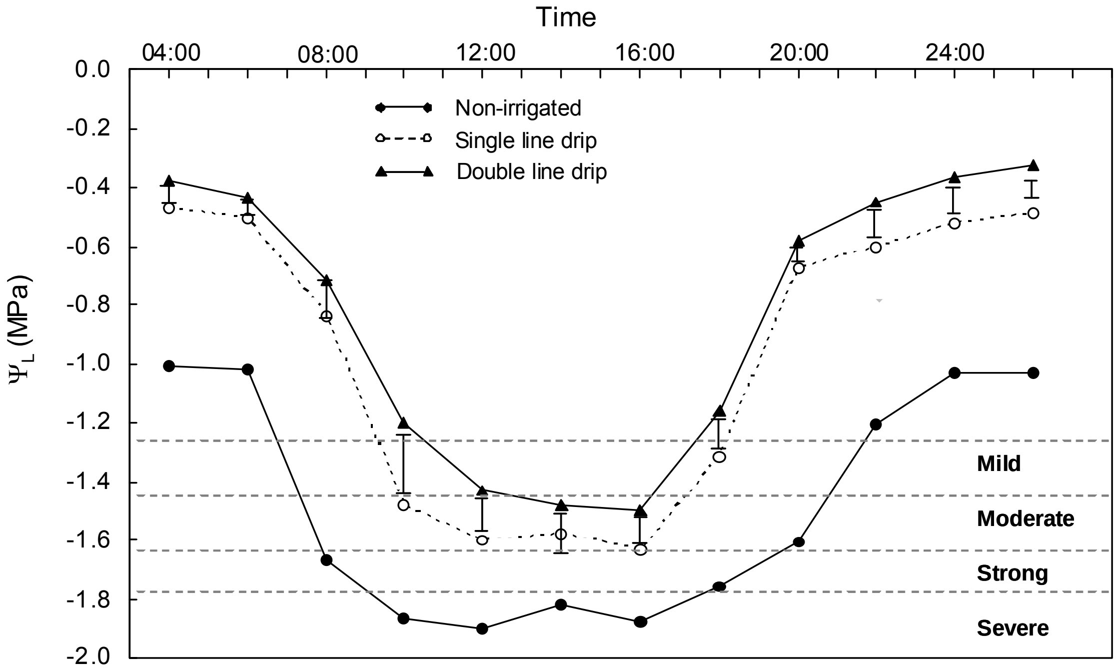

Figure 4.4. Effects of non-irrigated conditions and irrigation system on leaf water potential (Ψ_L) in Cabernet Sauvignon grapevines as measured on 28 January 2009 at Wellington. Vertical bars indicate the lowest significant difference ($p \leq 0.05$).

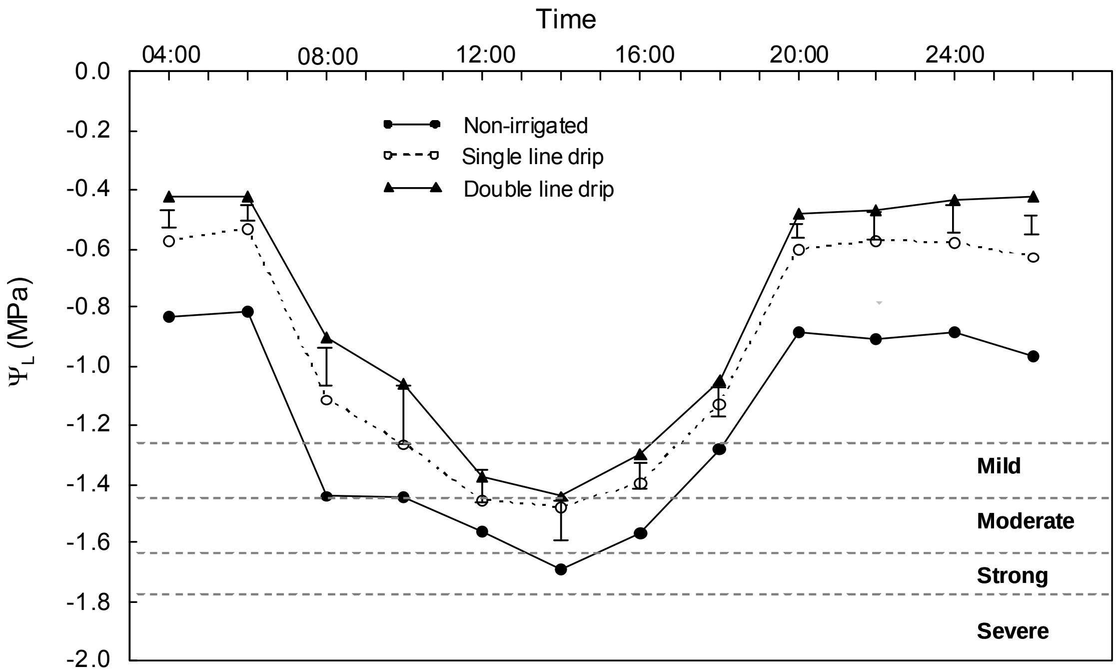

Figure 4.5. Effects of non-irrigated conditions and irrigation system on leaf water potential (Ψ_L) in Cabernet Sauvignon grapevines as measured on 28 January 2009 at Philadelphia. Vertical bars indicate the lowest significant difference ($p \leq 0.05$).

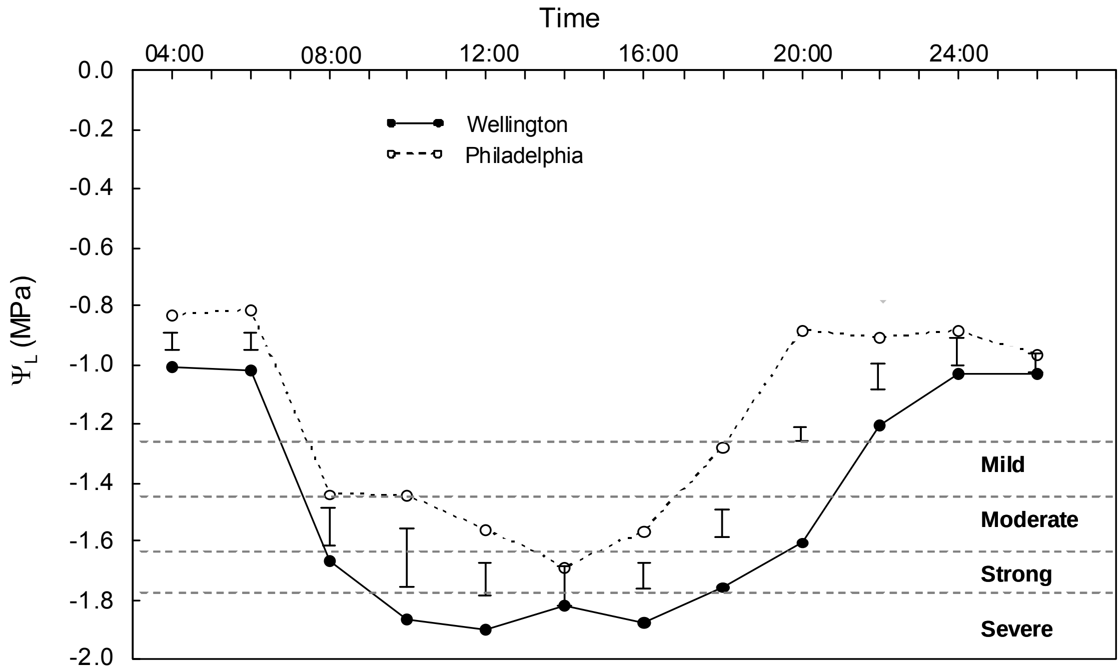

Figure 4.6. Diurnal leaf water potential (Ψ_L) in non-irrigated Cabernet Sauvignon at two localities as measured on 28 January 2009. Vertical bars indicate the lowest significant difference ($p \leq 0.05$).

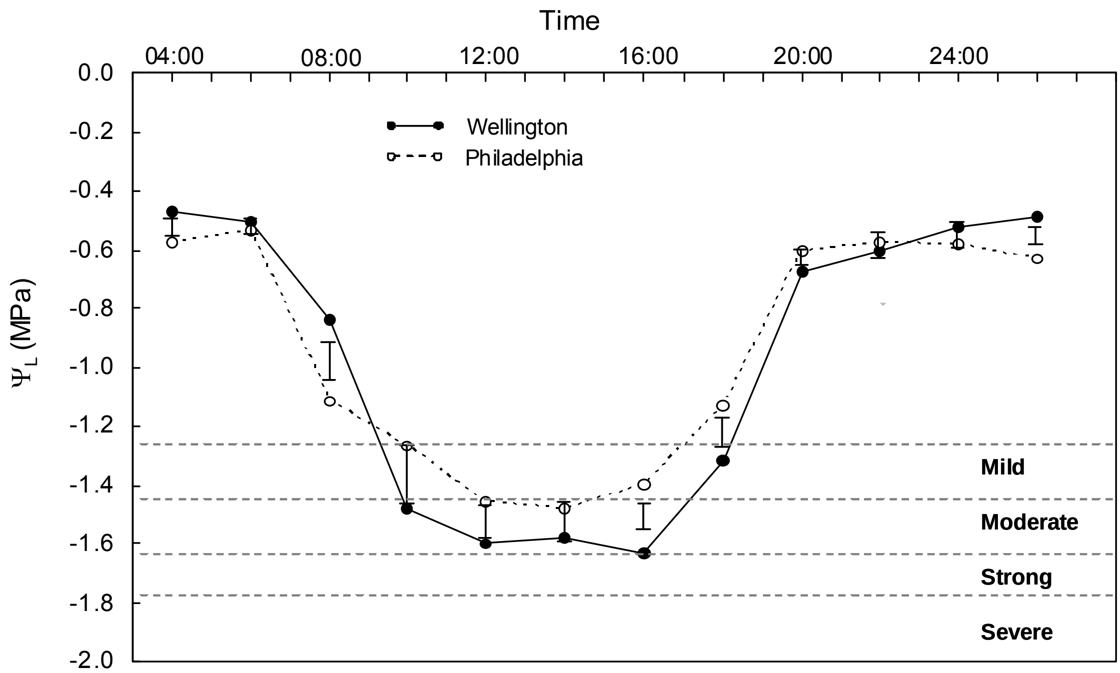

Figure 4.7. Diurnal leaf water potential (Ψ_L) in Cabernet Sauvignon irrigated by means of single drip lines at two localities as measured on 28 January 2009. Vertical bars indicate the lowest significant difference ($p \leq 0.05$).

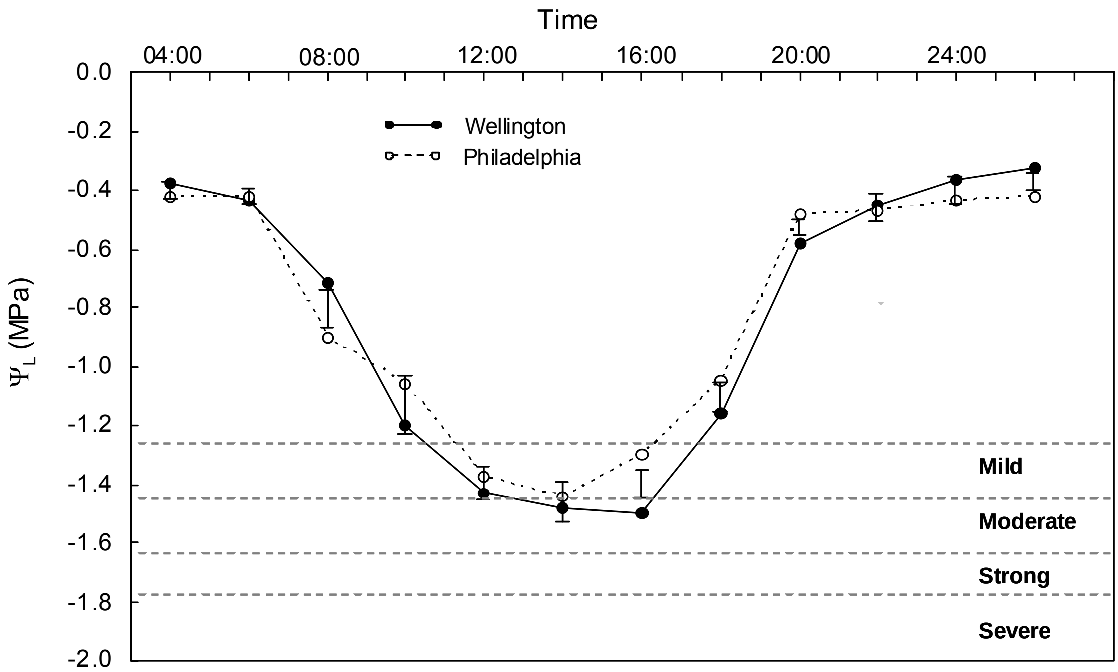

Figure 4.8. Diurnal leaf water potential (Ψ_L) in Cabernet Sauvignon irrigated by means of double drip lines at two localities as measured on 28 January 2009. Vertical bars indicate the lowest significant difference ($p \leq 0.05$).

Figure 4.9. Example of a non-irrigated Cabernet Sauvignon grapevine prior to harvest near Wellington.

Figure 4.10. Example of a non-irrigated Cabernet Sauvignon grapevine prior to harvest near Philadelphia.

Figure 4.11. Example of a single drip line irrigated Cabernet Sauvignon grapevine prior to harvest near Wellington.

Figure 4.12. Example of a single drip line irrigated Cabernet Sauvignon grapevine prior to harvest near Philadelphia.

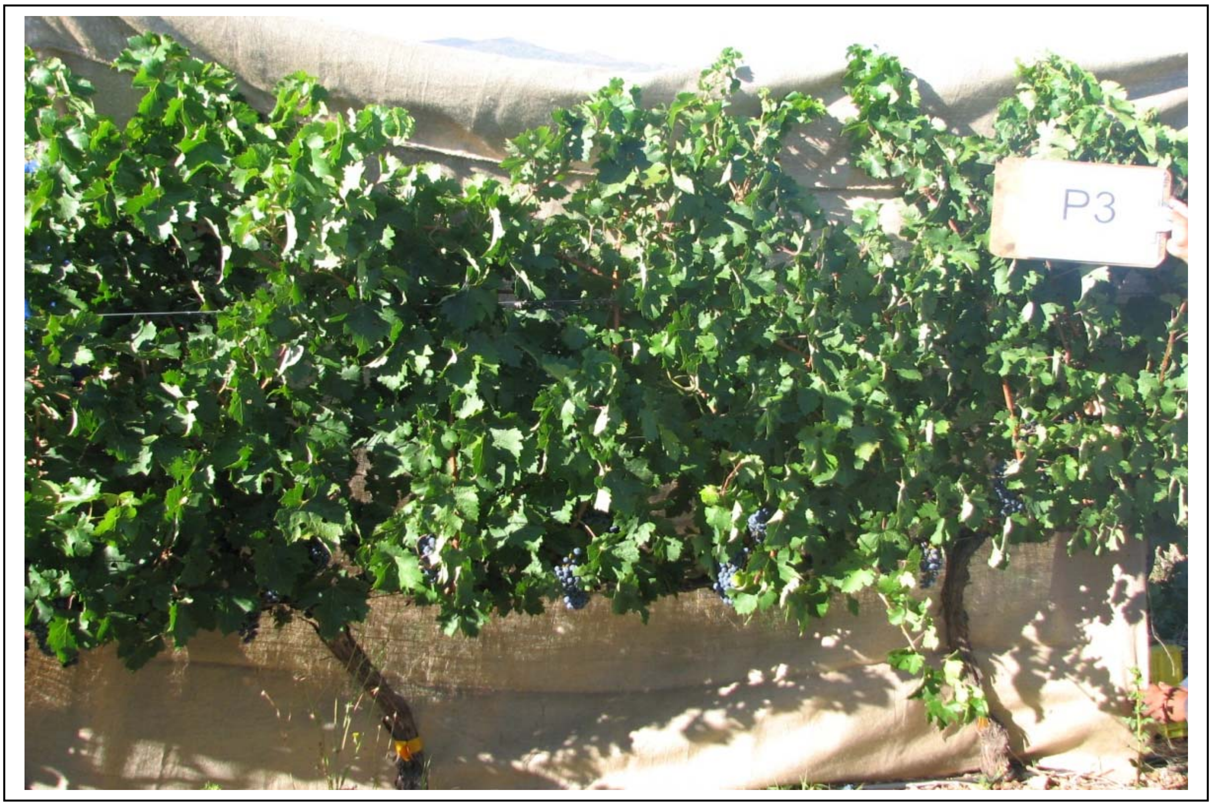

Figure 4.13. Example of a double drip line irrigated Cabernet Sauvignon grapevine prior to harvest near Wellington.

Figure 4.14. Example of a double drip line irrigated Cabernet Sauvignon grapevine prior to harvest near Philadelphia.

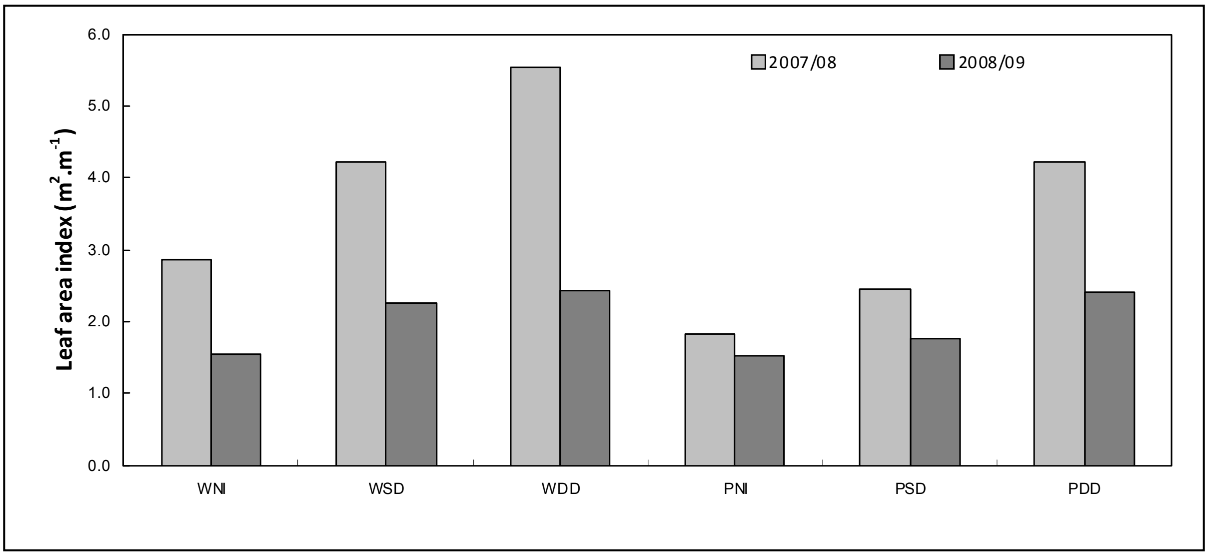

Figure 4.15. Leaf area index of Cabernet Sauvignon grapevines measured in six experiment plots in the Swartland region during the 2007/08 and 2008/09 seasons. Refer to Table 3.2 for description of plots.

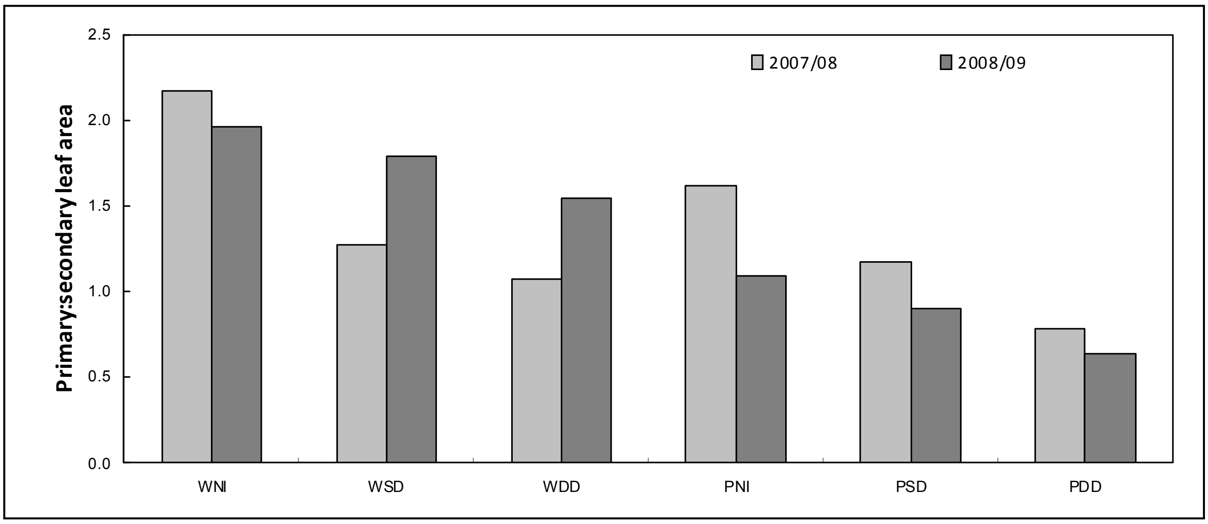

Figure 4.16. Ratio of primary leaves to secondary leaves of Cabernet Sauvignon grapevines measured in six experiment plots in the Swartland region during the 2007/08 and 2008/09 seasons. Refer to Table 3.2 for description of plots.

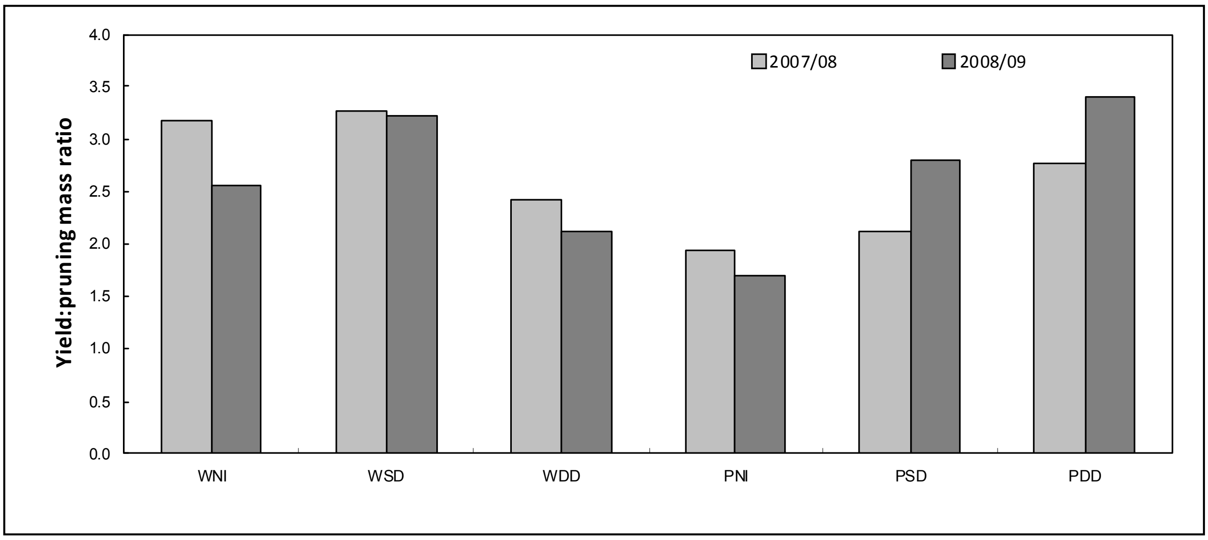

Figure 4.17. Yield to pruning mass ratio of Cabernet Sauvignon grapevines measured in six experiment plots in the Swartland region during the 2007/08 and 2008/09 seasons. Refer to Table 3.2 for description of plots.

Chapter 5

RESEARCH RESULTS

EFFECT OF CLIMATE AND SOIL ON GRAPE AND WINE CHARACTERISTICS OF CABERNET SAUVIGNON GRAPEVINES (*Vitis Vinifera* L.) AT TWO LOCALITIES IN THE SWARTLAND REGION

EFFECT OF CLIMATE AND SOIL ON GRAPE AND WINE CHARACTERISTICS OF CABERNET SAUVIGNON GRAPEVINES (*VITIS VINIFERA* L.) AT TWO LOCALITIES IN THE SWARTLAND REGION.

5.1 INTRODUCTION

Climate, and its components such as temperature, has an important role in the determination of wine style or quality (Le Roux, 1974; De Villiers *et al.,* 1996; Marais & Fourie, 1997; Bonnardot *et al.,* 2003; Hunter & Bonnardot, 2002; Van Leeuwen *et al.,* 2004; Van Leeuwen & Seguin, 2006). External factors such as climate, soil, topography and management modify the grapevine growth parameters such as flower initiation, set, yield, vegetative growth and microclimate (Jackson & Lombard, 1993). These factors alter the physiology of the berry by changing its composition and therefore final wine style and quality, as berry ripening is temperature sensitive. Yield and vegetative growth ratios can also contribute to slower sugar accumulation due to source/sink interaction (Winkler & Williams, 1939; Winkler *et al.,* 1974; Kliewer & Dokoozlian, 2005). According to Pandell (1999), total titratable acidity (TTA) in the grape juice at harvest was lower where grapes were produced in warmer climates, where higher temperatures generally accelerate malic acid respiration. Therefore, it can be expected that in the Western Cape, grapes grown in a warmer area further inland might potentially have lowered juice acidity and a higher pH. However, it should be noted that this relationship is also influenced by tartaric acid and potassium content in the grapes.

Véraison to harvest is the most important period for determining the grape and sensorial wine quality potential (Gladstones, 1992). The canopy environment during berry ripening is important, since the physiological and biochemical processes of the grapevine are temperature-sensitive. According to Buttrose *et al.* (1971), a temperature of 20˚C during the day promotes colour development in Cabernet Sauvignon grapes to a greater extent than day temperatures of 30˚C, due to anthocyanin biosynthesis being optimal within a range below this temperature. Berries exposed to continuous day temperatures of 20˚C during development tend to contain higher concentrations of malic acid, even when compared to berries exposed to higher temperatures for short periods (Buttrose *et al.*, 1971).

It can be accepted that climate will have a dominant effect on wine character in warm wine producing regions of the world (Winkler *et al.,* 1974; Vilanova *et al.,* 2007). In warmer regions, temperature and rainfall could have a pronounced effect on the wine style of different grape varieties (Bonnardot *et al.,* 2001). Carey (2002) showed that Cabernet Sauvignon vineyards in the Stellenbosch and Drakenstein areas in South Africa produced varied wine styles due to the seasonal variation in climate and the terroir effect. Berry volume and sugar accumulation are affected by many factors, namely plant water status, photosynthetic activity and temperature (Wang *et al.,* 2003 a,b). Sensorial grape quality was high on the soils that induced water deficits, particularly on clayey soils where water deficits in the season are moderate due to the higher water holding capacities (Van Leeuwen *et al.,* 2004).

The concept of sugar loading is a relevant approach that could be used as a physiological indicator of grapevine functioning, mainly relating to photosynthesis which is a reliable indicator of the temperature that the grapevine is subjected to and grape grapevine water status (Hunter & Deloire, 2005; Wang *et al*., 2003a; Deloire, 2009). Sugar loading can be defined as the evolution of the quantity of sugar per berry, expressed in mg per berry, from véraison onwards. Sugar in grape berries begins to rapidly accumulate from the moment they begin to soften at véraison (Coombe, 1992). The ratio of exposed leaf area to yield affects sugar loading via the phloem in the ripening berry (Wang *et al.,* 2003a). Kliewer & Weaver (1971) found that a leaf area to fruit weight ratio up to 1.4 m^2/kg optimised berry size, sugar and anthocyanin concentration. Grape sugar accumulation in the berry depends on the source (primarily photosynthesis) and sink activities in the grapevine Carbonneau & Deloire, 2001). The accumulation of sugars during maturation may occur through symplastic or apoplastic pathways (Coombe, 1992). Sugar accumulation in the berry primarily depends upon the photosynthetic activity of the grapevine, which when decreased under conditions of water restriction has been shown to result in a lower sugar unloading , since photosynthesis strongly depends upon leaf and grapevine water status, which in turn is dependent upon light and water availability (Wang *et al.* 2003 a).

Sugar accumulation in the reproductive sink represents the greater part of carbon uptake, and is a therefore a realistic indicator of the photo-assimilate quantity accumulating at the sink (Wang *et al.,* 2003a). Wang *et al.* (2003b) demonstrated a primary route of assimilate unloading by means of an *in vivo* experiment system which they called the “berry-cup” technique. The “berry cup” technique demonstrated that phloem unloading in ripening grape berries showing that glucose and fructose, in similar quantities, are the dominant sugars in the phloem unloading solution. It was observed that diurnal dynamics of sugar accumulation was similar for normally=watered and water-constrained grapevines during berry ripening. Since phloem unloading occurs in parallel to the process of photosynthesis, it is temperature and water sensitive. A key finding of Wang *et al.* (2003b) was that phloem sugar unloading was greater in normally-watered vines compared to water-constrained grapevines during ripening, because of the photosynthetic limitation under reduced grapevine water status. This phenomenon might account for the observed responses of grapevines to water constraints, namely stomatal closure, and reduced plant growth, fruit size and yield (Wang *et al.,* 2003b; Schultz & Matthews, 1993; Greenspan *et al*., 1994; Wang *et al.,* 2003a). Since both berry volume and sugar accumulation are affected by grapevine water status, photosynthesis and temperature the kinetic monitoring of the sugar loading, in mg sugar per berry, may be considered a relevant method of measuring the grapevine physiological functioning and in particular photosynthesis, which responds sensitively to ambient temperatures, depending on the plant water status (Hunter & Deloire, 2005; Deloire *et al.,* 2004; Wang *et al.,* 2003a; Carbonneau & Deloire, 2001; Carbonneau *et al*., 1998). According to these studies the kinetics of sugar loading is distinguished by three principle sugar loading profiles. The first stage is that of a continual and rapid loading, which occurs post-véraison whereby carbon sources are activated to supply the various sinks, primarily the berries and secondary shoots. The second stage is that of slowed sugar loading whereby the rate of ripening is inhibited. At this stage, an imbalance in the grapevine physiology, excessive water constraints or crop load in relation to the exposed leaves can severely restrict ripening (Carbonneau & Deloire, 2001). Thirdly, sugar loading reaches a plateau phase where active sugar loading observed at the previous two stages is followed by the cessation of sugar loading (Hunter & Deloire, 2005; Deloire *et al.,* 2005). The plateau is reached when the sugar loading is less than 3 mg per berry per day. In the light of this the sugar loading rate (mg per day) can be used to determine grapevine functioning at the physiological level. Sugar loading is calculated using sugar concentration and berry volume (McCarthy & Coombe, 1999; Brenon *et al.,* 2005; Hunter & Deloire, 2005). According to the ripening model described here, *i.e.* once the plateau of sugar loading has been reached, the evolution of ripening depends on other factors, namely cultivar, bunch microclimate, leaf to fruit balance, ratio of primary to secondary shoots and the climate during berry ripening (Bonnardot *et al.,* 2005; Carey, 2001; Hunter & Bonnardot, 2002). It has been shown that 20 days after the plateau has been reached, grapes express a fresh vegetative character, whilst 40 days after, grapes have a riper, cooked fruit character (Wang *et al.,* 2003a; Deloire *et al.*, 2008).

In addition to sugar accumulation, water constraints in grapevines can affect the metabolism of other primary and secondary compounds and their accumulation and transport to and into the berry. Therefore, water constraints have been shown to be a key factor influencing fruit composition (Wang *et al.,* 2003a). Anthocyanins are secondary metabolites in the berry and are responsible for the colour of red grape varieties and each variety has a particular anthocyanin profile. Most *Vitis vinifera* varieties produce non-acylated mono-glucosides, acetyl-glucosides, coumaroyl-glucosides which are derivatives of delphinidin, cyanidin, petunidin, peonidin and malvidin (Fournand *et al.,* 2006). Anthocyanin biosynthesis appears to increase with the increase in sugar loading, a co-regulation effect, reaching a plateau at a certain sugar concentration for each cultivar (Fournand *et al*., 2006). This study showed that the anthocyanin biosynthesis in Shiraz berries reached a plateau at a berry sugar concentration between 170-190 mg/ml, irrespective of the growing region. Free anthocyanin in the skins changed composition as the pulp sugar content increased. However, there was no increase in tannin content observed as sugars accumulated in the pulp (Fournand *et al.,* 2006). Furthermore, Bogs *et al.* (2005), showed that proanthocyanidin and anthocyanin biosynthesis may occur simultaneously in the berry skins.

The physical characteristics of soil, and in particular soil texture, as well as the colour, chemico-physical composition, pH_{KCl} and mineral composition thereof influences the wine composition (Fregoni, 1977). In terms of soil mineral composition, only the nitrogen (N) and potassium (K) content of the soil seemed to have a significant effect on wine composition (Saayman, 1992). Excess N has a negative effect on wine composition and indirectly effects wine composition due to excessive vegetative growth. Furthermore, carbohydrates are used for the vegetative growth at the expense of sugar accumulation. It has been shown that there was a pronounced sensorial vegetative character in Cabernet Sauvignon wines and the deep clay rich soils that are nutrient rich and have a high water holding capacity (Noble *et al.*, 1995). Previous research indicates that the effect of soil type on Cabernet Sauvignon wine sensorial style was less prominent with accurate irrigation scheduling (Olivier & Conradie, 2008).

The supply of water to the grapevine is one of the environmental factors that can affect berry size, and this may in turn influence the final wine style and quality (Ojeda *et al*., 2002). Irrigation has indirect effects on the juice composition and wine quality due to the effect on vegetative growth (Noble *et al.,* 1995; Choné *et al.,* 2001). Irrigation can manipulate vegetative growth due to the application of water that influence the soil water status, which in turn influences grapevine vegetative growth and yield. Grapevine water status induced by soil water status and interactively enhanced by warmer climatic conditions, has been shown to inhibit grapevine photosynthesis, plant growth, fruit size and yield (Wang *et al*., 2003b). Berry growth depends mainly on plant water supply and the accumulation of sugar in the berries depends on the source-sink and sink-sink relationships (Carbonneau & Deloire, 2001). According to Choné *et al.* (2001), early water deficits and lower N status throughout the growing season had beneficial effects on the total berry phenolic content and wine quality of Cabernet Sauvignon in the region Bordeaux in France. Berry size is water sensitive, and therefore indicative of the grapevine functioning in response to water constraints induced by deficit irrigation and climate changes. Water constraints applied before véraison, or later between véraison and harvest, can significantly modify the weight, diameter and volume of the grape berries through the influence of cell expansion (Ojeda *et al.,* 2001).

The overall sensory effect of ethyl propanoate, ethyl 2-methylpropanoate and ethyl 2-methylbutanoate was clearly established as the "black-berry" sensory characteristic (Pineau *et al.,* 2009). Whereas, the "red-berry" characteristics are contributed by ethyl butanoate, ethyl hexanoate, ethyl octanoate and ethyl 3-hydroxybutanoate as described by Pineau et al. (2009). The aromatic impacts of wines are based on perception thresholds determined in dilute alcohol solutions. Pineau *et al.* (2007) also showed that β-damascenone tended to enhance fruity notes of ethyl and masked the herbaceous aroma, suggesting that β-damascenone could have a more indirect impact on the red wine aroma (Pineau *et al*., 2007). β-damascenone is one of the more frequently mentioned compounds in studies of red wine aromas, and has been established as a key odorant in red wine extracts (Pineau *et al*., 2007).

Different irrigation strategies could influence the aroma and flavor differences in Cabernet Sauvignon wine (Olivier *et al.,* 2003; Chapman *et al.,* 2005). Water deficits that are established too rapidly or with a high intensity have a negative effect on grape yield and quality, decreasing the levels of sugar production and changing the secondary metabolism, conditioning the colour and gustative qualities of wine (Pellegrino *et al.,* 2004 references therein). Mild water deficit results in a fuller must and higher quality wine (Choné *et al.,* 2001), whilst higher tannin and anthocyanin content in red berries is related to moderate grapevine water deficits (Van Leeuwen *et al.,* 1994).

The aims of this study were to determine the effect of climate, soil and irrigation on (i) the rate of berry growth, sugar loading and anthocyanin accumulation as well as (ii) juice composition and sensorial wine quality potential of Cabernet Sauvignon grapevines growing at two localities in the Swartland region.

5.2 MATERIALS AND METHODS

5.2.1 EXPERIMENT LAYOUT

Grapevine water status was manipulated with irrigation restriction. Details of the experiment and plot layout, as well as soil and viticultural aspects are presented in Chapter 3. For the results documented in this chapter, grapevine water constraints were induced at two localities in the Swartland region, one at Wellington (W) and one at Philadelphia (P), to study the interactive effect of proximity to the ocean and soil water content. In the first plot, grapevines were cultivated non-irrigated (NI), whereas the second plot was irrigated with a single dripper line (SD) in the grapevine row. The third plot was irrigated using double dripper lines (DD), i.e. one in the grapevine row and the other in the middle of the work row. Plots will be referred to as, *e.g.* “PNI” for the non-irrigated grapevines near Philadelphia.

5.2.2 SAMPLING METHOD

The Cabernet Sauvignon berries were sampled on a weekly basis from pre-véraison (pea size) to harvest at each plot to monitor the progression of berry ripening. Four 50-berry samples were collected per plot from ten bunches per plot of twelve grapevines. Within this sample set, five bunches within and five outside the canopy were selected, with five berries sampled per bunch. For each bunch, one berry was sampled from the bottom of the bunch, two from the middle and two from the top. After sampling, berries were kept cool, in a cooler box to prevent sample degradation. The four sets of 50 berries which were weighed and the volume of the berries were determined by displacement of water in a volumetric measuring cylinder. One set of 50 berries was retained fresh and the remaining 3 samples frozen at -80°C for later analysis.

5.2.3 JUICE ANALYSES

The fresh 50-berry sample was used for the analysis of total soluble solids (TSS), total titratable acidity (TTA) and pH. These measurements were carried out on the same days as sampling. The berries were crushed using a household handheld liquidiser (Kambrock essential stick mix KSB7, Braun) three consecutive pulses, which ensured that seeds were not broken. The crushed berry and juice slurry was then centrifuged at 10 000 revolutions per minute for 10 minutes (Thermo Sorvall RC6). Thereafter, the centrifuged juice was poured through a small kitchen sieve and the skin and pulp lightly pressed. Total soluble solids were determined using a digital refractometer (Pocket PAL-1, Atago U.S.A. inc., Bellevue, WA, U.S.A.). Total titratable acidity and pH of the juice were measured using an automatic titrater (Metrohm 785 DMP Tritino, Metrohm AG, Herisau, Switzerland), against sodium hydroxide (NaOH) at a concentration of 0.33 N.

At véraison and harvest, grape juice was scanned using a mid infra red (MIR) spectrum (Winescan FT120 software version 2.2.1 Foss Electric A/S, Hillerod Denmark) to get more information on the ripening parameters and juice composition. Calibrations for grape juice have already been established by the Chemical Analytical facility at the Institute for Wine Biotechnology at the Department of Viticulture and Oenology, Stellenbosch University, Stellenbosch, South Africa. Sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg), as well as phosphorus (P) and total nitrogen (N) contents in juice samples collected at harvest. Were determined by a commercial laboratory (BEMLAB, Strand) according to their standard procedures.

5.2.3.1 SUGAR LOADING

Sugar loading was calculated on the basis of berry volume (or berry fresh mass) and sugar concentration (McCarthy & Coombe, 1999; Brenon *et al.,* 2005; Hunter & Deloire, 2005). Sugar loading formulas were used to calculate the sugar loading amount and rate using the Balling (˚B) and the berry volume, according to the standard calculation method (Deloire, 2009).

The sugar loading was calculated for a berry with a ripeness level of 25°B as follows (Deloire, 2009):

1. <u>Convert 25°B to probable alcohol:</u>

- 25 x 0.59 = 14.75° in probable alcohol, where 0.59 is the factor used for yeast activity to convert ˚B to predicted wine alcohol content).

2. <u>Determine mg of sugar per ml probable alcohol:</u>

To obtain 1° predicted alcohol, 17 g/L of sugar is required.

- 14.75° x 17 g/l =250.75 g/L, ≅250 mg of sugar/ml.

3. Calculate quantity of sugar per berry:

In addition to measuring °B, berry volume (or berry fresh mass thereof) is also measured to calculate sugar/ berry. A 50-berry sample was used to determine berry fresh mass for a representative berry population.

- 250 mg x volume of a berry (or the berry fresh mass thereof, because for many varieties there is a linear correlation between berry volume and fresh mass).

5.2.3.2 PHENOLIC COMPOUNDS IN GRAPES AND WINE

Three sets of the frozen 50-berry samples were used for analysis of phenolic compounds after 5-8 months in storage. To follow the evolution of the sugar loading and anthocyanin biosynthesis, only samples from the single drip treatment grapevines experiencing moderate water constraints were used. Seeds were removed from the berries while they were still frozen to prevent the loss of pericarp and juice. The skin and pericarp were weighed once the berries had thawed completely. Thereafter, the berries were homogenized using an Ultra-Turrax T25 high-speed homogeniser with an S25N Dispersing head (Janke & Kunkel GmbH & Co., Germany) at 24 000 revolutions per minute for two intervals of 120 seconds to prevent heating of the metal shaft. The extraction conditions used for phenolic compounds were essentially according to the method proposed by Iland *et al.* (2006). Anthocyanins were extracted from 1 g of homogenate in 10 ml 50% v/v aqueous acidified ethanol (pH 2) at 25˚C for an hour.

According to literature, the most suitable methods for extraction are methanol 70% at pH 1.5, extracting 95% of the anthocyanins. When using the Iland method, the anthocyanin extracts only provide relative values. This was deemed sufficient for this study as only viticultural treatments are being compared. The method proposed by Iland (2004) has been used with success with some modifications for optimisation by Jensen *et al.* (2007).

5.2.3.2.1 Spectrophotometry

The phenolic compounds for all the plots at both sites was measured at véraison and harvest using the spectrophotometer at 520 nm according to the procedures described by Iland *et al.* (2006).

5.2.3.2.2 Liquid chromatography

Only samples from the single drip treatment were measured using reverse phase high performance liquid chromatography (RP-HPLC). Reverse phase high performance liquid chromatography was performed on a Hewlett Packard Agilent 1100 series HPLC system equipped with a diode array detector (Agilent Technologies, Palo Alto, CA, USA). Data processing was done with Chemstation software (Hewlett Packard, Waldbronn, Germany). Separations were carried out on a polystyrene/divinylbenzene reversed phase column (PLRP-S, 100Ǻ, 150 × 4.6 mm, 3 µm) from Polymer Laboratories (Ltd) (Shropshire, UK) protected with a guard cartridge (PLRP-S, 10 × 4.6 mm) (Polymer Laboratories (Ltd), Shropshire, UK) with the same packing material. The following mobile phases were used, namely solvent A, containing de-ionised water with 1.5% v/v orthophosphoric acid (Reidel-de Haën) and solvent B consisting of 80% acetonitrile (Chromasolve, Reidel-de Haën) with 20% of solvent A. A linear gradient was used from 0 min, A 94%, B 6%; to 73 min, A 69%, B 31%; to 78, A 38%, B 62%, staying constant for 8 min to 86 min and then back to the starting conditions in 4 min to 90 min, A 94%, B 6%. A flow rate of 1 ml/min was used with a column temperature at 35^{o}C. This was adapted from the method proposed by Peng *et al.* (2002).

Phenols were quantified using external standards: (+)-catechin hydrate (Fluka), (-)-epicatechin (Sigma), gallic acid (Fluka), caffeic acid (Sigma), *p*-coumaric acid (Sigma), malvidin-3-glucoside (Polyphenols Laboratories AS, Norway), quercitin-3-glucoside (Fluka) and quercitin (Extrasynthése, France). Monomeric and dimeric flavanols and polymeric phenols were quantified at 280 nm as mg/L catechin units with a quantification limit of 1.5 mg/L, and epicatechin as epicatechin with a quantification limit of 1.5 mg/L. Cinnamic acids have a maximal absorbance at 316 nm and caftaric acid and caffeic acid were quantified as mg/L caffeic acid, while coutaric acid and *p*-coumaric acid were expressed as mg/L *p*-coumaric units with a quantification limit of 0.275 mg/L. Flavonol-glycosides and flavonol aglycones were quantified at 360 nm as respectively mg/L quercitin-3-glucoside and mg/L quercitin with a quantification limit of 0.05 mg/L. Anthocyanins, pigments and polymeric pigments were quantified at 520 nm as mg/L malvidin-3-glucoside with a quantification limit of 1.25 mg/L. The quantification limit for gallic acid was 0.25 mg/L.

The samples were thawed and centrifuged for 5 min at 14 000 rpm before injection. Thereafter, each sample was placed in a 1.5 ml dark coloured vial and protected from oxidation using N gas. The limit of quantification was determined as the smallest area that could be accurately integrated (< 3% standard deviation).

5.2.4 WINEMAKING

Forty kg grapes were picked from each plot and micro-vinified at the research winery of ARC Infruitec-Nietvoorbij. After the grapes were crushed, 50 mg/kg SO_2 was added. Skin contact was allowed for at least one hour before the crushed grapes were inoculated with a commercial wine yeast (VIN 13, Anchor Biotechnologies), at a concentration of 30 g/hL. Fifty g/hL diammonium phosphate (DAP) was then added. Fermentation was conducted on the skins at 25°C and the cap was punched down three times a day. The must was fermented down to between 0°B and 5°B. Following this, the skins were separated and pressed at *ca.* 0.2 MPa. The pressed wine was added to the free run-off wine and fermented at 25°C until dry. As soon as fermentation was completed, the wine was racked, the SO_2 adjusted to a total of 85 mg/L (in accordance with the analysis) and cold stabilised at 0°C for at least two weeks. After cold stabilisation the wine was filtered by using sterile mats (K900 and EK), as well as a 0.45 μm membrane and bottled into nitrogen filled bottles at room temperature. The total SO_2 was adapted during bottling to ensure that it was not less than 85 mg/L. The bottled wines were stored at 14°C until it was evaluated approximately six months later.

5.2.5 WINE SENSORIAL EVALUATION

Wines were subjected to sensorial evaluation by a trained panel of twelve experienced wine tasters from the South African wine industry. Wine characteristics were scored by means of a 100 mm unstructured line scale. The wines were ranked for each descriptor on a scale where the minimum score was "None", *i.e.* meaning that the attribute was not recognisable in the wine, to a maximum score of "Prominent". The sensory attributes ranked were visual colour, flavour, taste and overall wine quality. The flavour characteristics scored were (i) fresh vegetative aroma, *i.e*. herbaceous, fresh cut grass, green pepper, eucalyptus, mint, green beans, asparagus and olives, (ii) dry vegetative aroma, *i.e.* hay or straw, tea and tobacco, (iii) berry intensity, *i.e.* blackberry, raspberry, strawberry and blackcurrant and (iv) spicy aroma, *i.e.* liquorice, anise, black pepper and cloves. The taste characteristics were acidity, fullness (body) and astringency. The character and quality potential of the experimental wines was divided into the following classes: (i) $\leq$ 40% = poor (ii) > 40% to $\leq$ 50% = low (iii) > 50% to $\leq$ 60%, = medium (iv)

> 60% to ≤ 70% = high and (v) > 70% = exceptional (P.A. Myburgh, Personal communication, 2009).

5.2.6 WINE CHEMICAL EVALUATION

Following the sensorial evaluation, wines were analysed by a commercial laboratory (Integral Laboratories, Paarl). Residual sugar (RS), volatile acidity (VA), total acidity (TA), malic acid (MA), pH and alcohol contents of the wine was determined. The total phenolic profile of the wine was also determined. A 50 ml sample was drawn from the wine that had been used for the sensorial evaluation. This sample was used for HPLC analyses by the same method as for the berries. However, the phenolic profile in wines made from grapevines in all the plots was determined. The rest of the sample was used for the FT-IR spectra scan of the wines from all plots using a Winescan FT120 instrument.

5.2.7 STATISTICAL ANALYSES

Relationships between variables were determined by means of linear regression at the 95% confidence level using Statgraphics® Centurion XV (2005).

5.3 RESULTS AND DISCUSSION

5.3.1 BERRY VOLUME

For the Wellington site, berry volume typically decreased with increasing grapevine water constraints (Fig. 5.1A and 5.2 A). Berry volume was highest at the lowest water constraint with mean Ψ_s values of -0.72 MPa and -0.75 MPa for the 2007/08 and 2008/09 seasons, respectively. The difference in berry volume was 20% between non-irrigated and single drip, 40% between single and double drip, and 60% between non-irrigated and double drip line in the 2007/08 season (Fig. 5.1A). The difference was less prominent in the 2008/09 season, with 20% difference between WNI and WSD, 20% between WSD and WDD and 40% between non-irrigated and double drip (Fig. 5.2A). The large differences in berry volume between the treatments was a direct response to the water deficits placing constraints on grapevine functioning.

At the Philadelphia site, due to the moderate to cool seasonal conditions (refer to Chapter 3), no physiological response to the applied water deficits were observed. Hence, the final berry volume was similar between treatments, irrespective of the volume of water applied (Fig. 5.1B) in the 2007/08 season. Grape responses to moderate temperatures and humidity probably masked the effect of water application which in turn, reduced possible limitations to cell division and enlargement.

5.3.2 DESCRIPTIVE COMPARISON OF SUGAR DYNAMICS DURING BERRY RIPENING

5.3.2.1 Sugar concentration per mL juice

The evolution of sugar, expressed as a concentration in mg per millilitre juice, from véraison at the two localities for 2007/08 and 2008/09, is shown in Figures. 5.3 and 5.4. Sugar on a mg/mL basis increased throughout the ripening period, irrespective of the water constraints experienced by the grapevine. In the 2007/08 season, the single drip line irrigated grapevines near Wellington which experienced moderate water constraints, had higher sugar concentrations than berries from the other treatments at harvest (Fig. 5.3A). This effect was probably caused by an increase in sugar concentration when berry volume unexpectedly decreased prior to harvest (Fig. 5.1A). Due to the moderate water constraints experienced by the grapevines of all treatments near Philadelphia, there were no differences in sugar concentration (Fig. 5.4B). Sugar concentration (mg/mL) increased (Fig. 5.3 & Fig 5.4), even though berry volume did not necessarily increase (Fig. 5.1 and 5.2).

5.3.2.2 Sugar concentration per berry

The sugar loading expressed as content per berry at Wellington showed the same trend as berry volume in response to an increase in grapevine water constraints in both seasons (Fig. 5.5A and 5.6A). The different water applications induced three levels of water constraints, namely strong, moderate and mild constraints. The grapevines responded to each of the levels on a berry volume and probably photosynthetic level. There was a strong inhibition of grapevine functioning which resulted in three dynamics of berry ripening. The increased water constraints reduced stem water Ψ (refer to Chapter 4) which could have limited stomatal conductance, and hence a reduction in photosynthetic capacity (Van Leeuwen *et al.*, 2009). Since the restriction on physiological response of this treatment was sustained, it suggested that under the conditions observed at this particular locality, grapevines were not functioning optimally in terms of carbon assimilation. Therefore, water constraints could have limited photosynthesis. However, in spite of the concentration effect of smaller berries, the higher water constraint conditions resulted in lower sugar per berry. Wang *et al.* (2003a) concluded that the accumulation of sugar in the berry depends on the photosynthetic activity of the grapevine, which in turn depends on the water status of the plant throughout the day and over the ripening period. The double drip line irrigated grapevines at Wellington seemed to have functioned in a balanced fashion with regard to sugar per berry in both seasons. This indicated that the balance in grapevine vegetative and reproductive growth allowed sufficient functioning of sources to provide in the demand of the ripening sinks in the grapevine.

Near Philadelphia, results were not consistent for the two seasons, due to the second season being warmer which probably created a seasonal effect. In 2007/08, grapevines of the two drier treatments experienced moderate constraints, whereas the double line irrigated ones only experienced mild water constraints. However, there were no differences in sugar content per berry since there was probably no inhibition of photosynthesis. Although there were differences in water constraints (refer to Chapter 4), there was probably no effect on cell enlargement and grapevine functioning due to the moderate climate. In contrast to the first season, grapevines subjected to the lowest water constraints resulted in the highest sugar per berry in the 2008/09 season (Fig. 5.6B). This indicated that a limit on plant functioning was probably reached in the warmer season, which induced more prominent differences between treatments.

The foregoing results clearly illustrated the limitations of using sugar concentration in the juice as an indicator of grapevine functioning. Although the water constraints resulted in different berry volumes, it did not reflect in sugar concentration in the juice. Therefore, sugar concentration, expressed on a berry basis, should rather be considered as a more appropriate indicator of grapevine physiological functioning.

5.3.2.3 Sugar loading rate

Pervious research showed that grapevines which experienced no water constraints had a higher sugar unloading rate during ripening than water constrained grapevines (Wang *et al.,* 2003a). This could have been the major reason why the sugar concentration in the berries of the control grapevines was higher than in the water constrained berries. These results confirm that the dynamics of photosynthesis depend on the plant water status (Wang *et al.,* 2003a; Greenspan *et al.*, 1994; Schultz & Matthews, 1993). The regular increase, decrease and plateau of sugar loading rate was observed for all the treatments and localities (Fig. 5.7A & B & 5.8A), with the exception of the 2008/09 season at Philadelphia (Fig. 5.8B). The sugar loading plateau was not reached at this particular locality as the sugar was still being loaded at more than 3 mg/berry/day. The sugar loading plateau is considered to be reached when the sugar loading is less than 3 mg/berry/day (Deloire, 2009; Wang *et al*., 2003a&b). At Philadelphia, the plateau was probably not reached because cool climatic conditions only induced moderate water constraints (refer to Chapter 4). In addition, water supply to the grapevine might also have played a role, causing only partial inhibition by mild water constraints and promoting photosynthesis via irrigation. At Wellington, the sugar loading plateau was reached on 4 February 2008 (Fig 5.7A) and 9 February 2009 (Fig. 5.8B), therefore the grapevines seemed to be balanced as the ripening process was completed. The observed tendencies were similar to the typical berry ripening dynamics (Deloire, 2009 & Wang *et al.*, 2003a&b). At Philadelphia, the sugar loading plateau was reached just before 4 February 2008. The soil water status, which directly influences the grapevine water status (refer to Chapter 3), tended to dominate the climatic effect. However, sugar loading on a per day basis gave an indication of the influence of the climate. Since the climate had a major influence on vineyard evapotranspiration (refer to Chapter 3) it could have affected berry size. Therefore, the sugar content per berry was indirectly influenced, since it depended on the berry volume.

Grapes begin to accumulate sugar from berry softening (Coombe, 1992). In this study sugar loading rate increased with an increase in Ψ_S (Fig 5.9), which indicated that the water constraints in the grapevine played an important role in the grapevine functioning. Furthermore, the water constraint effect on sugar loading was more significant in the warmer area near Wellington compared to the cooler Philadelphia, which was closer to the Atlantic Ocean.

5.3.3 DESCRIPTIVE COMPARISON OF ANTHOCYANIN DYNAMICS DURING BERRY RIPENING

5.3.3.1 Anthocyanin content

The moderate water constraint conditions allows for optimal grapevine physiological functioning, situation known for even anthocyanin biosynthesis stimulation (Ojeda *et al*., 2001). Results from this study (Fig. 5.10 & 5.11) compare favourably to results obtained in a study with Shiraz, where anthocyanin biosynthesis reached a plateau at a sugar concentration of 170 mg/mL to 190 mg/mL, irrespective of the growing region (Fournand *et al*., 2006). For Cabernet Sauvignon in the Swartland region, anthocyanin biosynthesis reached a plateau when sugar levels in berries were between 200 mg/mL to 220 mg/mL (Fig. 5.10A, 5.10B & 5.11A). Near Philadelphia, the plateau for sugar loading was not reached in the 2008/09 season (Fig. 5.11B). When the relationship between anthocyanin and sugar content (mg/berry) near Wellington is considered, neither sugar nor anthocyanin concentration reached a plateau in the 2008/09 season (Fig. 5.11A). Anthocyanin biosynthesis increased parallel to the sugar until a specific sugar content was reached, whereafter, irrespective of an increase in sugar content, there was no further increase in anthocyanin biosynthesis. This typical parallel increase of sugar and anthocyanin (Fournand *et al*., 2006), and the subsequent decrease of anthocyanin biosynthesis at the sugar plateau, occurred near Wellington in both seasons (Fig 5.10A & 5.11A). Near Philadelphia this trend only occurred in the first season (Fig. 5.10B).

5.3.3.2 Anthocyanin loading

In both seasons, the rate of sugar and anthocyanin loading were typical to the sugar loading model of Wang *et al.* (2003a) near Wellington (Fig. 5.12A & 5.13A), but for only one season near Philadelphia (Fig. 5.12B). Anthocyanin biosynthesis typically followed the increases and decreases in sugar loading rate. This trend occurred because anthocyanin biosynthesis requires sugar (Davies & Robinson, 1996; Robinson & Davies, 2000). It is interesting to note that in the 2008/2009 season there was an apparent co-regulation of sugar and anthocyanin accumulation in the grapes near Philadelphia. Previous studies on anthocyanin biosynthesis showed a strong co-regulation of the two pathways at a molecular level (Vivier & Pretorius, 2002), and it would appear that the current results support this observation. At the molecular level, both temperature and water constraints have been shown to influence gene expression in the anthocyanin pathway, irrespective of a direct association with sugar accumulation (Wang *et al.,* 2003a; Ojeda *et al.,* 2001; Schultz & Matthews, 1993; Greenspan *et al.,* 1994). However, due to the physiological implications of strong water constraints on sugar loading, as observed at Wellington, the current results appear to demonstrate a stronger influence of water application on anthocyanin metabolism than the effect of temperature. This observation is further supported by the work Ojeda *et al,* (2002) confirming that berry size influences phenolic content and proved that anthocyanin biosynthesis in the berries can be limited by intense water deficit applied during the period between anthesis and véraison. The availability of water better explains the observed effects on the berry volume, whereas the photosynthetic activity, which relates to the ratio of leaf area to yield quantity, accounts for the effects on phloem sugar unloading in the ripening grape berry (Boss & Davies, 2001)..

The conclusion drawn is that the inhibition of source functioning is caused by temperature constraints and plant water status as a result of soil water status. The inhibition of the source function is the decrease of photosynthetic activity as a result of either temperature or water constraint conditions. Also, the inhibition of sucrose functioning in the grapevine is due to both disaccharide transporters and monosaccharide transporters being affected by various parameters including light, water and ion status, wounding, hormones, fungal and bacterial attack (Kühn *et al.,* 1997). Therefore, sugar accumulation in the grape berry is regulated by complex mechanisms (Conde *et al.,* 2007; Fillon *et al.,* 1999).

5.3.4 TOTAL COLOUR AND PHENOLIC COMPOUNDS AT VÉRAISON AND HARVEST

The total colour (red pigments) and phenolics per berry was higher in the 2008/09 season, but it should be noted that due to methodology changes, analysis of the 2007/08 grapes were stored at -20˚C for the first half and at -80˚C for the second half of the year, analysis took place *ca.* a year after harvest, whereas analysis of the 2008/09 grapes were stored only at -80˚C and analysis were carried out four months after harvest (Table 5.1). The lower total colour and phenolics in the 2007/08 season may have been due to degradation of colour and phenolic compounds after prolonged storage (Cynkar *et al.,* 2004). For this reason, results from the 2008/09 season will be the focus of the discussion. The other factor contributing to the higher colour and phenols in the 2008/09 season may have been the higher temperature inducing slightly more water constraints (Fig. 5.14).

Studies have shown that the measurement of grape colour could act as a predictor of eventual wine colour. Total red colour at véraison (50% total colouring per bunch) and at harvest for both localities in 2007/08 season is presented in Figure 5.14. At véraison in 2008/09, the colour and phenolics was higher near Wellington, which indicated that, due to the warmer climate, the grapes near Wellington started to ripen before grapes at the cooler climate near Philadelphia (Fig 5.15). The interactive effect of water and temperature was already seen at véraison. The highest colour at véraison was near Wellington for the single drip line irrigated grapevines whereas near Philadelphia the non-irrigated treatment induced the most colour (Fig. 5.14). At véraison, the grapevines in the warmer climate required some irrigation to maintain moderate water constraints, whereas in the moderate climate, no additional water was required to maintain water constraints optimal for balanced ripening. At harvest in

2008/09, the highest levels of anthocyanin in the berries at both localities occurred in the berries of the double drip line irrigated grapevines, it could be that anthocyanin content may have been on the decline in the other treatments. Although anthocyanin biosynthesis in berries near Wellington tended to start earlier than near Philadelphia, berries from the cooler climate tended to have higher colour and phenolics at harvest.

In the 2008/09 season, the total phenolics in berries were higher near Wellington at véraison and higher near Philadelphia at harvest. This trend was the same for all levels of water constraints (data not shown). Thus, in a cooler climate such as at Philadelphia, phenolic development in berries increased towards the end of the season. The total phenolics in the berries were more sensitive to storage, water and temperature compared to total colour. The total berry colour showed no difference between the 2007/08 and the 2008/09 season, regardless of the prolonged storage time (Fig. 5.14 & Fig. 5.15). These results suggested that anthocyanin biosynthesis was more sensitive to atmospheric conditions than to water constraints under the given conditions. This was in agreement with earlier findings (Ojeda *et al.,* 2001).

5.3.5 JUICE COMPOSITION AT HARVEST

The harvest date variation between the two localities (Table 5.2) was result of the interactive effect of climate and soil water content. The aim was to harvest the grapes as close to 24˚B as possible. The reasoning for selecting 24˚B as the optimal ripeness for this study was so that the sugar content of the experimental sample was similar to that of commercially harvested grapes in the Swartland region. However, it was noted at the outset that a predetermined ˚B for optimal ripeness has been demonstrated as irrelevant while the sugar loading plateau is more relevant (Deloire *et al*., 2005; Deloire, 2009 & Wang *et al*., 2003a&b). This aim was not achieved at all the sites e.g. Wellington in 2007/08 where the maximum sugar concentration was between 20.6˚B and 21.6˚B, for the WNI and WDD respectively. (Table 5.2). In cases like this, grapes were harvested to prevent further fruit deterioration under the hot weather conditions. Sugar loading in non-irrigated grapevines at Wellington probably slowed down because of water constraints and hot climate. In the case of double drip line irrigation sugar loading probably stopped because of the high level of water availability. Excessive water resulted in active vegetative growth (refer to Chapter 4) which probably acted as a stronger sink for photosynthates compared to the ripening fruit.

According to Winkler *et al.* (1974), seasonal conditions, particularly temperature in terms of heat summation, influence the rate of grapevine development. The seasonal influences observed in this study were identical to those displayed between hot and cool regions. The 2008/09 season at Wellington was hotter compared to the 2007/08 season, and so the grapes ripened to the desired TSS. In 2008/09, ripening also occurred at a more rapid rate which caused harvest to be earlier than in 2007/08. At Philadelphia, grapes did not reach the target sugar concentration of 24˚B in the 2007/08 season, due to the more moderate climate relative to Philadelphia (Winkler *et al*., 1974) and excessive water. Due to low water constraints, there was still significant vegetative growth observe in grapevines at harvest. In 2008/09, grapes of the non-irrigated treatment near Philadelphia were harvested a week earlier than the irrigated ones. The non-irrigated and single drip line irrigated grapevines at Philadelphia reached the ripeness level of 24˚B in the second season, but due to the excessive vegetative growth induced by double drip irrigation the desired ˚B was not reached in these grapes. Climatic differences between the two localities in the second season were reflected in harvest dates. Harvest was up to 13 days later at the cooler locality. As the distance from the Atlantic Ocean decreased, the effect of the cooler, more moderate atmospheric conditions seemed to retard the sugar accumulation (Table 5.2 & 5.3). The high yields (Table 4.12) could also have slowed down the sugar accumulation due to sink competition (Winkler & Williams, 1939; Winkler *et al.,* 1974; Kliewer & Dokoozlian, 2005; Van Schalkwyk & Archer, 2008).

The juice TTA at harvest was lower near Wellington in comparison to Philadelphia (Table 5.2 & 5.3) which was probably due to the warmer atmospheric conditions at Wellington. Tartaric and malic acid is reduced via respiration and, therefore, grapes grown in warmer climates typically contain lower acidity levels in comparison to cooler climates (Pandell, 1999). This was confirmed by the tartaric and malic acid contents as determined by the Winescan method (Table 5.3). At Wellington, non-irrigated conditions may have created constraints that resulted in decreased acidity. At Wellington, TTA was lowest in grapes produced by non-irrigated grapevines in both seasons.

The pH in a solution is a measure of the active acidity, therefore pH will increase with a decrease in the TTA. High pH often results in unstable musts and wine (Conde *et al*., 2007) since the must and wine is more susceptible to oxidative and microbial spoilage at higher pH. In 2008/09, where grapes at both localities were harvested at similar ripeness, grapes from near Wellington had higher pH than those from near Philadelphia (Table 5.2).

The sugar content, in mg/mL, was highest in grapes produced by single drip irrigated grapevines near Wellington in 2007/08 (Table 5.2). These grapevines had the highest yield to pruning mass ratio, which could have created an optimal environment for the balanced functioning of the grapevine allowing the highest sugar accumulation. The lowest sugar content in mg/ml occurred in the second season near Philadelphia in the double drip irrigated grapevines. This was due to a high level of water availability, and the moderate climate. Therefore the vegetative growth was vigorous, *i.e.* slightly shaded and still growing actively at the end of the ripening season. However, when the sugar was expressed on a per berry basis, grapes of the double drip line treatment at Wellington had the most sugar per berry in both seasons (Table 5.2). The berry volume of these grapes was the highest due to higher water availability, confirming the sensitivity of berry volume to grapevine water status. In the case of Philadelphia, the highest sugar content per berry occurred in the non-irrigated grapevines. However, at this locality berry volumes were comparable as the moderate climate masked the effect of water status on berry volume. Due of the cooler climate at Philadelphia, the non-irrigated grapevines functioned more optimally since only moderate constraints were induced, resulting in sugar content (mg/berry) being higher compared to the irrigated grapevines.

The mineral content of the juice at harvest differed with climate and soil water content (Table 5.4). At both localities, juice P was lower in 2008/09 in comparison to 2007/08. This could possibly be attributed to warmer conditions and less soil water. At both localities, must P were highest in the double drip treatment. The juice K contents were much lower at harvest in 2008/09 than in 2007/08. Juice K content was only higher in the case of double drip grapevines near Philadelphia in 2008/09. The Na content did not show any consistent trends. However, must Na was substantially higher at Philadelphia compared to Wellington. The only plausible explanation for this could be that the Na content was approximately 20% times higher in the soil near Philadelphia compared to Wellington (Table 3.4). The extremely high Na value obtained in the 2007/80 season for the double drip irrigated grapevines near Philadelphia could be an experimental error. Juice Mg was less in 2008/09 in comparison with 2007/08. There were no clear trends regarding locality or water status. Similarly, juice N showed no clear trends, irrespective of locality and season. Should juice N be lower than 130 mg/L, fermentation problems may occur as yeasts cells require this N level as a minimum to sustain fermentation (Holzapfel & Treeby, 2007). Similar to other ions, Ca tended to be higher in the juice of the berries produced in the cooler area.

5.3.6 WINE ANALYSES

The anthocyanin profile, as well as the total anthocyanins in the berry as determined by means of the RP-HPLC analysis, showed that the total anthocyanin in the wine increased as the water constraint in the grapevine decreased near Wellington for both seasons and Philadelphia in 2008/09 (Table 5.5). This was probably due to the increasing canopy density resulting from more vigorous growth (refer to Chapter 4). At Wellington in particular, the cooler canopy micro climate caused by more leaves provided the best conditions for anthocyanin biosynthesis. Other studies have shown that shading causes a decrease in anthocyanin biosynthesis (Joscelyne *et al.,* 2007; Downey *et al.,* 2004). However, the increase in the canopy density at Wellington probably created a cooler micro climate with sufficient light penetration into the canopy, and therefore, a more favourable environment for anthocyanin biosynthesis (Table 5.5).

Wine alcohol, pH, TA, volatile acidity (VA) (legal limit of 1.2 mg/L), residual sugar (RS), K, anthocyanin and polyphenol contents did not show any significant trends with respect to the locality and irrigation strategy during the two seasons (Table 5.6). The colour hue (A420 nm/A520 nm) of the wine is an indication of the it’s dominant pigments and the optical density of A420 nm and A520 nm is a useful indicator of the browning of the wine due to oxidation and the anthocyanin concentration, respectively. The wine colour hue tended to increase to a maximum of 0.9 as the water constraints in the grapevine became less with the increased water applied (data not shown). This trend was more pronounced near Wellington. The colour hue could have resulted from an indirect effect due to shading and unfavourable canopy micro climatic conditions of the grapevines in response to the irrigation. The negative effect of wine colour could be caused by the effect of K on wine pH which affects the properties of the anthocyanin in the wine (Condé *et al.,* 2007). The lower the pH of the medium, the more the anthocyanins will be in the red form. Non-irrigated conditions tended to increase wine colour intensity during both seasons. This could have been caused indirectly by the reduction of vegetative growth resulting from water deficits. Consequently, the improved canopy micro climate, particularly with respect to more light, could have promoted anthocyanin biosynthesis. Grapevines experiencing water deficits produce generally smaller berries, which increases the skin to pulp ratio. Furthermore, the effect of grapevine water status on anthocyanin concentration is also due to the differential growth response of the skin and inner mesocarp tissue, or direct stimulation of phenolic biosynthesis (Condé *et al*., 2007).

It has been shown by Archer & Strauss (1989) that shading can reduce the skin colour of Cabernet Sauvignon berries. Marais (2005) concluded that poor colouring of grapes eventually has negative effects on overall wine quality. The wine colour, as expressed in total anthocyanin in mg/L, tended to increase with a decrease in water constraints at Wellington, but this trend was not so obvious near Philadelphia. The tendency towards better wine colour near Wellington, clearly illustrated the importance of irrigation in such a hot climate. In general, the anthocyanin concentration in wines from Wellington was higher than those from Philadelphia. Therefore it seemed that the warmer climate tended be more favourable for the biosynthesis of anthocyanins. Moderate water constraints, irrespective of climate, produced the best quality wine. This trend was in agreement with previous studies, as moderate water constraints induced by limited irrigation could be desirable for wine colour development compared to grapevines that experienced either too much, or no water constraints.

5.3.7 WINE SENSORIAL CHARACTERISTICS

The sensorial wine colour was generally approximately 30% higher in the 2008/09 season compared to the 2007/08 season in the warmer climate (Table 5.8). Wine colour was from 7% to 30% higher in the 2008/09 season in the cooler climate. Wines from Wellington had better colour than those produced near Philadelphia. Wine colour tended to decrease with the application of water, probably due to an increase in vegetative growth, shading and accumulation of anthocyanins being restricted. However, wines produced from single drip line grapes at Wellington had the best sensorial colour which ranged between 65.9% in 2007/08 and 93.1% in 2008/09 seasons, respectively. These results once again emphasises the importance of irrigation in a warmer climate to alleviate water constraints. At Philadelphia, wines with the best colour were produced from grapes of the non-irrigated treatment as the water constraint level was moderate, thereby limiting excessive vegetative growth in comparison to the irrigated grapevines. The canopies of the non-irrigated grapevines had more exposure to sunlight, and conditions were therefore more suitable for the accumulation of red pigments.

Wines did not differ with respect to acidity, fresh and cooked vegetative character and spicy intensity (Table 5.8). However, wines from Wellington had the most intense berry character when grapes were cultivated without irrigation. Similar tendencies were observed for the wines produced Philadelphia. Water conditions have long been recognised as an important factor determining wine grape quality, thereby affecting wine sensory attributes (Koundouras *et al.,* 2006). The water applied is one factor that can influence berry size and which in turn, influences the nature and amount of phenolics in the grape and finally in the wine, due to the concentration effect of more skin to berry flesh (Ojeda *et al.,* 2002). Grapevine water status affects fruit growth and concentration of total phenolics and wine sensory attributes and is an important tool to manipulate final wine quality in many parts of the world (Kennedy, 2002). The differences in berry character could have been caused by the chemical breakdown, or formation, of berry flavours due to the grapevine water status (Condé *et al.,* 2007).

In the warmer locality, single line drip irrigation tended to increase wine fullness, whilst in the cooler locality, fullness increased with reduced water application (Table 5.8). Wine fullness was higher in 2008/09 compared to 2007/08. There was a good agreement between overall sensorial wine quality and fullness (Fig. 5.16). Overall sensorial wine quality potential varied between all the treatment plots on the basis of certain characteristics that had been deemed necessary for quality of these Cabernet Sauvignon wines (Table 5.8). In past studies, it has been concluded that soil type has no effect on wine overall quality, but rather, that it has an influence on certain components in grapes and the wine (Rankine *et al.,* 1971). In this study the soil as a factor in wine quality can be eliminated since the soil physical and chemical properties were comparable at the two localities.

Overall wine quality in 2007/08 near Wellington ranged from medium to low potential, whilst for 2008/09, wine quality ranged from medium to high wine potential (Table 5.8). The better wine quality in the 2008/09 season at Wellington could be attributed to the warmer climatic conditions causing grapevines to experience more water constraints over a longer period (Fig. 4.3 & 4.4). Near Philadelphia, grapes produced medium to low potential wines in the 2007/08 and 2008/09 seasons, respectively. In 2008/09 wines also tended to be better than in 2007/08. This could also probably be attributed to the warmer conditions in 2008/09 (Fig 3.2).

Overall quality of the single drip line wines from Wellington was 51.1% and 65.5%in 2007/08 and 2008/09, respectively. This wine quality was obtained where the mean Ψ_M over the two ripening seasons ranged from -0.05 MPa in December to -0.10 MPa in March (Fig. 3.1). During the ripening period, the mean Ψ_S and Ψ_L was -0.97 MPa, -1.44 MPa and -1.10 MPa, -1.56 MPa for 2007/08 and 2009/08 respectively (Table 4.5 & 4.6). The water constraint threshold classes were moderate (Table 4.1). The grapevine water status resulted in a mean leaf area per meter cordon of 7.0 m^2 and 3.8 m^2, a mean leaf area index of 4.2 and 2.3, and a mean fruit to leaf balance of 0.4 and 0.8, for the

2007/08 and 2008/09 season, respectively (Table 4.6). Cane lengths were 1.6 m and 1.1 m, mean pruning mass of 3.7 t/ha and 3.6 t/ha (Table 4.8), mean berry mass of 1.3 m and 1.1 m, bunch mass of 0.12 kg and 0.10 kg, and a yield of 12.1 t/ha and 11.6 t/ha, for the 2007/08 and 2008/09 season respectively. Visually, the grapevine appeared balanced, with healthy mature leaves and active shoot growth stopped at ripening (Fig. 4.3). The results show that the increased plant water constraint in the 2008/09 season caused leaf area index to decrease by approximately 50%, and the fruit to leaf balance to increase by 50%. The increased water constraint placed a limit on the vegetative growth in the 2008/09 season and resulted in the grapevine being more balanced, producing a wine of medium to high quality. The cane length and the pruning mass was less in the 2008/09 season, indicative of the grapevine being more balanced. Berry mass, bunch mass and yield was less in the 2008/09 season compared to the 2007/08 season. In spite of this, wines for both seasons were classed into the medium to high potential wine quality. This was due to the water constraint being moderate in both seasons, but in the 2008/09 season, the climatic conditions were hotter and this induced more water constraint, which increased the wine potential to within 4% of the high quality potential class. The reason for the increase in the overall quality of non-irrigated and double drip line wines is the same as discussed above for the single drip line. When taking the water status of the grapevine into account, the wine quality was lower for wines made from the grapevines of the non-irrigated and double drip line. Water constraints induced were too severe in the 2008/09 season, retarding grapevine functioning. In contrast, water constraints were too low for the double drip lines the hotter climatic conditions inducing more water constraint and the application of water reducing the water constraint. These results confirm the importance of water in hotter climates to reduce the water constraints to moderate levels so that the grapevine can function.

Overall wine quality of non-irrigated treatments near Wellington was 44.9% and 50.4% in 2007/08 and 2008/09, respectively. The wine quality was obtained where the mean Ψ_M over the two seasons ranged from -0.06 MPa in December to -0.16 MPa in March (Fig. 3.11). During the ripening period, the mean Ψ_S and Ψ_L was -0.98 MPa, -1.46 MPa and -1.13 MPa, -1.54 MPa for 2007/08 and 2008/09, respectively (Table 4.5 & 4.6). This falls into the moderate water constraint threshold class (Table 4.1). The grapevine water status resulted in a mean leaf area per meter cordon of 9.7 m^2 and 3.5 m^2 per grapevine, a mean leaf area index of 4.2 and 1.5, and a mean fruit to leaf balance of 0.3 and 0.6 for 2007/08 and 2008/09, respectively (Table 4.6). Cane lengths were 1.2 m and 1.1 m, mean pruning mass of 4.6 t/ha and 4.4 t/ha (Table 4.8), mean berry mass was 1.5 g and 1.0 g, bunch mass was 0.19 kg and 0.15 kg, and a yield of 7.2 t/ha and 7.5 t/ha for the 2007/08 and 2008/09 seasons, respectively. Visually, excessive grapevine shoots growth occurred throughout the season. Although the growth was fairly balanced, there was a tendency towards more vegetative, rather than reproductive growth (Fig. 4.2).

The results show that the increased plant water constraints in the 2008/09 season caused the leaf area index to decrease by *ca.* 65%, and the fruit to leaf balance to increase by 65%. The increased water constraints placed a limit on the vegetative growth in the 2008/09 season and resulted in more balanced grapevines, producing a wine of medium to low quality for the irrigation treatments and medium quality for the non-irrigated. However, the pruning mass was less in the 2008/09 season, indicative of the grapevines being more balanced. In addition, the berry mass and bunch mass was lower in the 2008/09 season compared to the 2007/08 season. Yield for both seasons was similar. Wine quality for the non-irrigated treatment was similar over the two seasons and is a result of the moderate climate. The increase in wine quality in 2008/09 can also be attributed to an increase in wine colour and fullness. In contrast to Wellington generally producing medium to high quality wine, only non-irrigated grapevines produced acceptable wine quality near Philadelphia in both seasons.

The wine quality produced by single and double line drip irrigated grapevines near Philadelphia was lower in 2007/08 compared to 2008/09. However, wines of both seasons were still classified as of poor quality. This was probably caused by the water constraints being too low (Fig. 3.12). This suggested that irrigation eliminated any water constraints that might have been favourable by limiting the vegetative growth of the grapevine in the moderate climate. The non-irrigated conditions in the moderate climate, with close proximity to the Atlantic Ocean only induced moderate water constraints. Irrigation of these naturally moderately constrained grapevines reduced the water constraints into the mild category. This level of water constraint seemed to be insufficient to induce for optimal ripening in a moderate climate. According to Conradie (2002), water constraints will be the most important factor that could reduce wine quality in non-irrigated or low frequency irrigated grapevines in sandy soil, as the soil dries out faster. The soil near Philadelphia is a sandy loam soil which has a higher water holding capacity than sandy soils. However, the soil was still sensitive to water losses caused by the prevailing environmental conditions.

The best wines were produced from grapes grown at the warmer locality. Even at the same level of water constraint, the warmer climatic conditions further inland resulted in wines of higher quality. Wines produced from non-irrigated grapevines at both localities had the best sensorial colour as well as the best quality.

5.4 CONCLUSIONS

A decrease in distance to the ocean, and therefore cooler, more moderate climate induced minimal water constraints in the grapevines. Therefore, ripening also occurred earlier near Wellington than near Philadelphia. However, at both localities, the harvest date was water constraint related, with grapevines experiencing moderate water constraints reaching the desired target sugar level of 24˚B for harvest. Due to the three water constraint classes which influenced sugar accumulation and berry ripening, harvest dates for the treatments near Wellington differed by as much as seven days. The water constraints influenced berry volume. In contrast to Wellington, only one class of water constraint occurred near Philadelphia. Since, berries of all the treatments had the same volume and sugar content, there was probably no water related effects on cell enlargement and grapevine functioning at this locality. The foregoing indicated that the grapevine water status influenced berry volume and rate of berry ripening.

Excessive vegetative growth occurred in the case of double drip line irrigated grapevines near Wellington and Philadelphia in the first season. Sugar loading did not reach a plateau in grapes produced by these vigorous grapevines. The vegetative growth probably acted as a sink to the detriment of sugar loading into the berries. The negative impact of severe water constraints was evident in non-irrigated grapevines near Wellington in the first season. The desired sugar level could not be reached, probably because severe water constraints and high temperatures caused the inhibition of photosynthesis. Sugar concentration (mg/ml) was the highest where grapevines were subjected to moderate water constraints. These grapevines appeared to be more balanced in terms of yield to pruning mass ratio which enhanced sugar accumulation, probably due to improved photosynthesis and carbohydrate utilization.

At Wellington, a strong inhibition of grapevine functioning related to water content was evident, but it did not reflect in sugar concentration in the juice. Similar to previous findings, the results indicated that juice sugar concentration increases throughout the season were not always as a result of sugar loading, but may also be due to a concentration effect because of smaller berries resulting from grapevine constraints.

Therefore, berry sugar loading seemed to be a more reliable indicator of grapevine functioning than juice sugar concentration.

Anthocyanin content in the grapes, as quantified on a per berry basis, showed that sugar and anthocyanin were co-regulated. Anthocyanin biosynthesis reached a plateau when the sugar content per berry ranged between 200 mg/ml to 220 mg/ml. Moderate water constraints induced by single drip line irrigation near Wellington and no irrigation near Philadelphia produced the highest colour at véraison. However, at harvest, grapes from the cooler climate tended to have the highest colour and phenolics, as anthocyanin biosynthesis was favoured by the cooler temperatures of approximately 20˚C.

Moderately constrained grapevines, with balanced vegetative and reproductive growth, which allowed more exposure to sunlight and grapevine functioning required for optimal ripening of all berry components, produced the best sensorial wine colour. The sensorial wine quality increased with an increase in the fullness of the wine. Moderately constrained grapevines, irrespective of locality, also produced the best overall sensorial wine quality. This trend was in agreement with previous studies, which concluded that moderate water constraints induced by restricted irrigation can be desirable for both wine colour and quality.

5.5 LITERATURE CITED

Archer, E. & Strauss, H.C. (1989). Invloed van oorskaduwing op die prestasie van Cabernet Sauvignon. *Wynboer*, September 1989, 10-11.

Bogs, J., Downey, M. O., Harvey, J.S., Ashton, A. R., Tanner, G.J. & Robinson, S.P. (2005). Proanthocyanidin synthesis and expression of genes encoding leucoanthocynidin reductase and anthocyanin reductase in developing grape berries and grapevine leaves. *Plant Physiol.* **205**, 652-663.

Bonnardot, V., Carey, V., Planchon, O. & Cautenet, S. (2001). Sea breeze mechanism and observations of its effects in the Stellenbosch wine producing area. *Wineland*. October 2001, 107-113.

Bonnardot, V., Planchon, O., Carey, V.A. & Cautenet, S. (2003). Diurnal wind, relative humidity and temperature variation in the Stellenbosch-Groot Drakenstein wine growing area. *S. Afr. J. Enol. Vitic*. **23**, 61-71.

Bonnardot, V., Planchon, O. & Cautenet, S. (2005). Sea breeze development under an offshore synoptic wind in the South-Western Cape and implications for the Stellenbosch wine-producing area. *Theo. Appl. Clim*. **81**, 203-218.

Boss, P.K. and Davies, C. (2001) Molecular biology of sugar and anthocyanin accumulation in grape berries. In *Molecular Biology and Biotechnology of the Grapevine* (Roubelakis-Angelakis, K.A., ed) pp. 1–34, Kluwer Academic Publishers

Brenon, E., Bernard, N., Zebic, O. & Deloire, A. (2005). Grape maturity: Proposal for a method using the berry volume as indicator. *Revue des oenologues*. **117**, 1-3.

Buttrose, M.S., Hale, C.R. & Kliewer, W.M. (1971). Effect of temperature on the composition of 'Cabernet Sauvignon' berries. *Am. J. Enol. Vitic.* **22**, 71-75.

Carbonneau, A. (1998). Aspects qualitatifs, 258-276. In Proc. XXVIIth World Congress of Vine and Wine. Bratislava. Traité d'irrigation, Tiercelin J.R., Lavoisier Tec et Doc ed., p. 1011.

Carbonneau, A. & Deloire, A., (2001). Plant organization based on source-sink relationship: new finding on development, biochemical and molecular responses to environment. Molecular *Biology & Biotechnology of grapevine*. 263-280.

Carey, V. A., (2001). Spatial characteristic of natural terrior units for viticulture in the Bottelaryberg-Simonsberg-Helderberg winegrowinf area. M.Sc. Agric Thesis. Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Carey, V.A. (2002). Cultivar x environment interaction: example of Cabernet Sauvignon in the Stellenbosch-Drakenstein wine growing area, South Africa. Paper presented at the OIV Groupe d'Experts: Zonage Vitivinicole, March 2002, Paris.

Chapman, D.M., Roby, G., Ebeler, S., Guinard, J-X & Matthews, M.A. (2005). Sensory attributes of Cabernet Sauvignon wines made from vines with different water status. *Austr. J. Grape & Wine Research* **11**, 339-347.

Choné, X., Van Leeuwen, C., Chéry, P. & Ribéreau-Gayon, P. (2001). Terroir influence on water status and nitrogen status of non-irrigated Cabernet Sauvignon (*Vitis vinifera*). Vegetative development, must and wine composition (Example of a Medoc Top Estate Vineyard, Saint Julien Area, Bordeaux, 1997). *S. Afr. J. Enol. Vitic.* **22**, 8-15.

Conde, C., Silva, P., Fontes, N., Dias, A.C.P., Tavares, R.M., Sousa, M.J., Agasse, A., Delrot, S. & Gerós, H. (2007). Biochemical changes throughout grape berry development and fruit and wine quality. *Food Global Science Books* **1,** 1-22.

Conradie, K. (2002). Grondvorm kan wynstyl grootliks beïnvloed: Cabernet Sauvignon uit Durbanville en Robertson. *Wineland*, November 2002, 107-109.

Coombe, B.G. (1992). Research on development and ripening of the grape berry. *Am. J. Enol. Vitic.,* **43**, 101-110.

Cynkar, W.U., Cozzolino, D., Dambergs, R.G., Janik, L. & Gishen, M. (2004). The effects of homogenisation method and freezing on the determination of quality parameters in red grape berries of *Vitis vinifera. Austr. J. Grape & Wine Research.* **10**, 236-242.

Davies, C. & Robinson, S.P., (1996). Sugar accumulation grape berries. Cloning of two putative vacuolar inveratse cDNA and their expression in grapevine tissues. *Plant Physiology*. **111**, 275-283.

Deloire, A. (2009). The concept of berry sugar loading. *Dept of Vitic & Enol, Stellenbosch University.*

Deloire, A., Carbonneau, A., Wang, Z. & Ojeda, H. (2004). Vine and water. *J. Int. Sci. Vigne Vin* **38**, 1-13.

Deloire, A. & Hunter, J.J. (2005). Berry composition as affected by bunch exposure. *Progres Agricole et Vitic.* **122**, 151-157.

Deloire, A., Kelly, M. & Bernard, N. (2008). Managing harvest potential:Navigating between terroir and the market. *31st conference of the South Agrican Society for Enology and Viticulture.* Somerset West, 11-14 November.

Deloire, A., Vaudour, E., Carey, V., Bonnardot, V. & Van Leeuwen, C. (2005). Grapevine responses to terroir: A global approach. *J. Int. Sci. Vigne Vin.* **39**, 149-162.

De Villiers, F.S., Schmidt, A., Theron, J.C.D. & Taljaard, R. (1996). Onderverdeling van die Wes-Kaapse wynbougebiede volgens bestaande klimaatskriteria. *Wynboer*, January 1996, T10-T12.

Fillon, L., Ageorges, A., Picaud, S., Coutos-Thevenot, P., Lemoine, R., Romieu, C. & Delrot, S., (1999). Cloning and expression of a hexose transporter gene expressed during ripening of grape berry. *Plant Physiology* **120**, 1083-1094.

Fournand. D., Vicens. A., Sidhoum. L., Souquet. J., Moutqunet. M. & Cheynier. V. (2006). Accumulation and extractability of Grape Skin Tannins and Anthocynins at different advanced physiological stages. *J. Agric. Food Chem.* **54**, 7331-7338.

Fregoni, M. (1977). Effects if soil and water on the quality of the harvest. In: Proc. Int. Sym. Quality of the vintage, February 1977, Cape Town, South Africa, 151-168.

Gladstones, J. (1992). History of climate selection for Australian viticulture. Viticulture and Environment. Winetitles, Adelaide. p. 4-7.

Greenspan, M.D., Shackel, K.A. & Matthews, M.A. (1994). Developmental changes in the diurnal water budget of the grape berry exposed to water deficits. *Plant Cell Environment,* **17**, 811-820.

Harbertson, J. & Spayd, S. (2006). Measuring phenolics in the winery. *Am. J. Enol. Vitic*. **57**,280-288.

Holzapfel, B.P. & Treeby, M.T. (2007). Effects of timing and rate of N supply on leaf nitrogen status, grape yield and juice composition from Shiraz grapevines grafted on one to three rootstocks. *Austr. J. Grape & Wine Research.* 13, 14-22.

Hunter, J.J. & Bonnardot, V., (2002). Climatic requirements for optimal physiological processes: A factor in viticultural zoning. In: Proc. 4th Int. Symp. on Viticultural Zoning, 17-20 June 2002, Avignon, France, p.553-565

Hunter, J.J. & Deloire, A. (2005). Relationship between sugar loading and berry size of ripening Syrah/R99 grapes as affected by grapevine water status. Gesco XIVeme journees du groupe europeen d'etude des systems de conduit de la vigne, Geisenheim, Allemagne, 23-27, 127-133.

Iland, P.G., Cynkar, W., Francis, I.L., Williams, O.J. & Coombe, B.G. (1996). Optimisation of methods for the determination of total and red-free glycosyl glucose in black grape berries of *Vitis vinifera. Austr. J. Grape & Wine Research.* 2, 171-178.

Iland, P.G., Ewart, A., Sitters, J., Markides, A. & Bruer, N., 2000 (1st ed). Determination of red pigments (colour) and total phenolics of grape berries. In:Techniques for chemical analysis and quality monitoring during winemaking. Patrick Iland Wine Promotions, Australia. pp. 78-79.

Jackson, D. I. & Lombard, P. B. (1993). Environmental and management practices affecting grape composition and wine quality. A review. *Am. J. Enol. Vitic.* 44, 4, 209-430.

Jensen, J.S., Blachez, B. & Egebo, M. (2007). Rapid extraction of polyphenols from red grapes. *Am. J. Enol. Vitic.* 58, 451-461.

Joscelyne, V.L., Downey, M.O., Mazza, M. & Bastian, S.E. (2007). Partial shading of Cabernet Sauvigon and Shiraz vines altered wine color and mouthfeel attributes, but increased exposure had little impact. *J. Agric. Food Chem.* **55**, 10888-10896.

Kennedy, J. (2002). Understanding grape berry development. Practical Winery & Vineyard July/August 2002.

Kliewer, W.M. & Dokoozlian, N.K. (2005). Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. *Am. J. Enol. Vitic*. **56**, 170-181.

Kliewer, W.M. & Torres, R.E. (1972). Effect of controlled day and night temperatures on grape coloration. *Am. J. Enol. Vitic.* **23**, 71-77.

Kliewer, W., & Weaver, R. (1971). Effect of crop level and leaf area on growth, composition and coloration of Tokay grapes. *Am. J. Enol. Vitic*. **22**, 172-177.

Koundouras, S., Marinos, V., Gkoulioti, A., Kotseridis, Y. & Van Leeuwen, C. (2006). Influence of vineyard location and grapevine water status on fruit maturation of non irrigated c*v* Agiorgitiko (Vitis *vinifera* L.). Effects on wine phenolic and aroma components*. J. Agric. Food Chem*. **54**, 5077-5086.

Le Roux, E.G. (1974). A cliamtic categorisation of the South African Western Cape wine producing areas. [Title in Afrikaans: 'n Klimaatsindeling van die Suidwes-Kaaplandse Wynbougebiede]. *M.Sc. Agric Thesis*. Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Marais, J. (2005). Relationship between grape colour and wine quality. *Wynboer*, August 2005.

Marais, J. & Fourie, E. (1997). Druiftemperatuur: 'n Belangrike kwaliteitsparameter. *Wynboer*, October 1997, T8-T9.

McCarthy, M.G. & Coombe, B.G. (1999). Is weight loss in ripening grape berries cv. Shiraz caused by impeded phloem transport. *Austr. J. Grape & Wine Research.* **5**, 17-21.

Noble, A.C., Elliotfisk, D.L. & Allen, M.S. (1995). Vegetative flavor and methoxypyrazines in Cabernet Sauvignon. *Fruit Flavors.* **596**, 226-234.

Ojeda, H., Andary, C., Kraeva, E., Carbonneau, A. & Deloire, A. (2002). Influence of pre- and post véraison water deficits on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. *Am. J. Enol. Vitic.* **53**, 261-267.

Ojeda, H., Deloire, A. & Carbonneau, A. (2001). Influence of water deficits on grape berry growth. *Vitis.* **49**, 3, 141-145.

Olivier, M.P. & Conradie, W.J. (2008). Effect of soil type on Sauvignon blanc and Cabernet Sauvignon wine style at different localities in South Africa. In: Proc. VIIth International Terroir Congress, 19-23 May 2008, Nyon Switzerland, 96-101.

Oliviera, C., Silva Ferreira, A.C., Pinto. M., Hogg, T., Alves, F. & Guedes de Pinho, P. (2003). Carotenoid compounds in grapes and their relationship to plant water status. *J. Agric. Food Chem.* **51**, 5967-5971.

Pandell, A.J. (1999). The acidity of wine. http://www.wineperspective.com/the_acidity_of_wine.htm Date of access: 25 Augustus 2009.

Patrick, J.W., (1990). Sieve elements unloading: cellular pathway, mechanism and control. *Physiology Plant.* **78**, 298-308.

Pellegrino, A., Lebon, E., Voltz, M. & Wery, J. (2004). Relationship between plant and soil water status in vine (*Vitis vinifera L.). Plant and Soil.* **266**, 129-142.

Peng, Z., Iland, P.G., Oberholster, A., Sefton, M.A., Waters, E.J. (2002). Analysis of pigmented polymers in red wine by reverse phase HPLC. *Aust. J. of Grape and Wine Research.* **8**, 70-75.

Pineau, B., Barbe, J.-C., Van Leeuwen, C. and Dubourdieu, D. (2007). Which impact for B-Damascanone on red wine aroma? *J. Agric. Food Chem*., **55**, 4103-4108.

Pineau, B., Barbe, J.-C., Van Leeuwen, C. and Dubourdieu, D. (2009). Examples of perceptive interactions involved in specific "red-" and "black-berry" aromas in red wines. *J. Agric. Food Chem.,* 57, 3702-3708.

Rankine, B.C., Fornachon, J.C.M., Boehm, E.W. & Cellier, K.M. (1971). Influence of grape variety, climate and soil on grape composition and on the composition and quality of table wines. *Vitis.* **10**, 33-50.

Robinson, S.P. & Davies, C. (2000). Molecular biology of grape berry ripening. *Austr. J. Grape & Wine Research.* **6**, 175-188.

Saayman, D. (1992). Natural influences and wine quality. Part 2: The role of soil. *Wynboer*, August 1992, 49-51.

Schultz, H.R. & Matthews, M.A., (1993). Growth, osmotic adjustment, and cell-wall mechanism of expanding grape leaves during water deficits. *Crop Science.* **33**, 287-294.

Van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S. & Dubourdieu, D. (2004). Influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic*. **55**, 207-217.

Van Leeuwen, C. & Seguin, G. (2006). The concept of terroir in viticulture. *Journal of Wine Research.* **17**, 1-10.

Van Leeuwen, C. & Seguin, G. (1994).Incidences de l'alimentation en eau da la vigne, appréciéé par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (*Vitis vinifera* variété Cabernet franc, Saint-Emilion, 1990). *J. Int. Sci. Vigne Vin*. **28**, 81-110.

Van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D. and Gaudillere, J.-P. (2009). Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? *J. Int. Sci. Vigne Vin*. **43**, 121-134.

Van Schalkwyk, D. & Archer, E. (2008). Die effek van alternatiewe snoeimetodes op die wingerd- en wynkundige prestasie (Deel I): Cabernet Sauvignon in die Stellenbosch area. *Wineland*, July 2008, 84-91.

Vilanova, M. Zamuz, S., Vilanino, M. & Sieoro, C. (2007). Effect of terroir on the volatiles of Vitis vinifera cv. Albarino. *Journal of the Sci of Food & Agric.* **87**, 1252-1256.

Vivier, M.A. & Pretorius, I.S. (2002). Genetically tailored for the wine industry. *Trends in Bio-technology* **20**, 472-478.

Wang, Z.P., Deloire, A., Carbonneau, A., Federspiel, B. & Lopez, F. (2003a). Study of sugar phloem unloading in ripening grape berries under water constraint conditions*. J. Int. Sci. Vignee et Vin.* **37**, 213-222.

Wang, Z.P., Deloire, A., Carbonneau, A., Federspiel, B. & Lopez, F. (2003b). An in vivo experimental system to study sugar phloem unloading in ripening grape berries during water deficiency constraint. *Annals of Botany.* **92**, 523-528.

Winkler, A.J., Cook, J.A., Kliewer, W.M. & Lider, L.A. (1974). General Viticulture Second Edition. University of California Press, p. 143-144.

Winkler, A.J. & Williams, W.O. (1939). The heat required to bring Tokay grapes to maturity. *Proc. Am. Soc. Hort. Sci.* **37**, 650-652.

Table 5.1. Total colour and phenolic compounds in Cabernet Sauvignon grapes produced in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	Véraison colour (mg anthocyanin/berry)					
2007/08	0.19	0.36	0.26	0.33	0.30	0.28
2008/09	0.84	1.16	0.84	0.55	0.08	0.19
	Véraison phenolics (absorbance/berry)					
2007/08	0.22	0.28	0.23	0.28	0.26	0.26
2008/09	0.46	0.60	0.47	0.32	0.16	0.18
	Harvest colour (mg anthocyanin/berry)					
2007/08	0.92	1.08	0.93	1.00	1.21	1.08
2008/09	1.63	1.57	1.72	1.69	1.74	1.77
	Harvest phenolics (absorbance/berry)					
2007/08	0.63	0.70	0.63	0.62	0.73	0.61
2008/09	0.87	0.86	0.99	0.89	0.99	1.02

[1] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 5.2. Total soluble solids (TTS), total titratable acidity (TTA), pH, berry volume and sugar contents in Cabernet Sauvignon grapes in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
			Harvest date			
2007/08	03-Mar-08	26-Feb-08	03-Mar-08	26-Feb-08	26-Feb-08	26-Feb-08
2008/09	11-Feb-09	11-Feb-09	17-Feb-09	17-Feb-09	24-Feb-09	24-Feb-09
			TSS (ºB)			
2007/08	20.6	23.7	21.6	22.9	22.1	21.7
2008/09	23.2	24.3	24.5	24.6	24.6	21.6
			TTA (g/L)			
2007/08	5.24	5.27	6.24	6.64	6.57	7.11
2008/09	4.63	6	5.93	6.99	6.99	8.88
			pH			
2007/08	3.73	3.7	3.65	3.7	3.7	3.6
2008/09	3.62	3.44	3.88	3.44	3.44	3.44
			Volume/berry (cm^3)			
2007/08	0.9	1.0	1.3	1.0	1.0	1.1
2008/09	0.9	1.1	1.2	1.0	0.7	0.7
			Sugar (mg/ml)			
2007/08	206.62	237.71	216.65	229.69	221.66	217.65
2008/09	232.70	243.73	245.74	246.74	246.74	216.65
			Sugar (mg/berry)			
2007/08	185.96	237.71	281.64	229.69	221.66	239.42
2008/09	209.43	268.10	294.88	246.74	177.65	145.15

[1] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 5.3. Grape juice analyses two weeks prior to harvest of Cabernet Sauvignon grapes produced in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

	Locality					
	Wellington			Philadelphia		
	WNI[(1)]	WSD	WDD	PNI	PSD	PDD
	Gluc-Fruc (g/L)					
Pre harvest	257	253	238	186	188	210
Harvest	237	251	254	255	251	237
	Total soluble solids (ºB)					
Pre harvest	24.6	24.3	23.2	18.9	19.1	20.9
Harvest	23.1	24.2	24.5	24.5	23.9	24.4
	Density (mg/L)					
Pre harvest	1.11	1.11	1.10	1.08	1.08	1.09
Harvest	1.10	1.10	1.11	1.11	1.10	1.11
	Total titratable acidity (g/L)					
Pre harvest	3.54	4.07	4.90	8.01	7.85	6.97
Harvest	3.10	3.69	4.02	4.71	5.99	6.23
	pH					
Pre harvest	3.38	3.25	3.17	3.01	2.98	2.95
Harvest	3.67	3.5	3.81	3.53	3.29	3.27
	Malic acid (g/L)					
Pre harvest	1.0	1.7	2.8	6.8	6.1	4.3
Harvest	1.0	1.3	1.8	2.2	2.9	4.6
	Tartaric acid (g/L)					
Pre harvest	5.2	5.8	5.6	6.2	6.8	7.5
Harvest	5.8	6.2	7.3	8	8.6	7.5
	Volatile acidity (g/L)					
Pre harvest	0.50	0.38	0.31	0.14	0.17	0.25
Harvest	0.41	0.41	0.36	0.31	0.27	0.47
	Alpha amino acids (mg/L)					
Pre harvest	101	88	78	80	77	37
Harvest	137	111	167	125	92	138

[(1)] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 5.4. Juice analysis at harvest of Cabernet Sauvignon grapes produced in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	N (mg/L)					
2007/08	323	694	91	124	215	155
2008/09	194	98	275	240	153	291
	P (mg/L)					
2007/08	123.0	108.0	159.9	180.4	150.9	143.0
2008/09	106.1	35.8	116.7	85.6	85.7	127.1
	Ca (mg/L)					
2007/08	35.3	52.4	29.8	59.6	51.3	50.9
2008/09	40.4	34.2	38.9	69.6	50.2	46.2
	Mg (mg/L)					
2007/08	126.7	110.7	114.7	126.9	109.3	117.9
2008/09	81.6	62.5	94.2	115.1	87.0	85.7
	K (mg/L)					
2007/08	7475.8	1934.4	5299.2	1405.1	1876.7	1638.9
2008/09	1686.1	783.5	1141.2	713.6	887.4	1842.1
	Na (mg/L)					
2007/08	4.6	15.1	9.7	210.2	63.4	45.2
2008/09	8.8	9.8	5.2	37.0	77.8	39.1

[1] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 5.5. Analyses of Cabernet Sauvignon wines ptoduced in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
			Total Anthocyanin (mg/L)			
2007/08	219.8	278.2	337.5	215.9	236.6	259.3
2008/09	306.5	391.3	434.3	310.2	328.8	350.9
			Total Glucoside (mg/L)			
2007/08	137.3	173.2	216.1	136.1	147.6	170.4
2008/09	189.2	238.3	252.6	199.7	208.8	217.1
			Total Acetagluc (mg/L)			
2007/08	64.9	81.9	94.8	67.4	76.0	77.7
2008/09	101.0	132.5	164.2	94.2	103.1	115.5
			Total Coumgluc (mg/L)			
2007/08	17.6	23.0	26.6	12.4	13.0	11.2
2008/09	16.2	20.5	17.5	16.3	16.8	18.2
			Malv-3-Glucoside (mg/L)			
2007/08	117.1	141.8	173.0	114.8	130.9	128.4
2008/09	153.8	185.4	200.5	140.9	162.9	166.6
			Quer-galactoside (mg/L)			
2007/08	1.0	2.4	2.6	-	1.0	5.6
2008/09	23.6	27.9	10.8	11.6	13.3	13.7
			Quer-3-glucoside (mg/L)			
2007/08	14.5	17.9	19.2	9.5	7.1	24.3
2008/09	14.1	16.9	37.1	44.1	30.5	22.9
			Quercetin (mg/L)			
2007/08	12.8	4.5	12.2	3.0	2.0	5.5
2008/09	3.9	3.2	2.6	3.3	5.7	2.3
			Total flavanols (mg/L)			
2007/08	56.7	62.8	50.4	46.6	55.7	65.6
2008/09	34.8	27.2	45.2	40.9	16.6	19.5
			Total Polyphenols (mg/L)			
2007/08	300.4	295.3	395.6	384.6	346.4	320.2
2008/09	150.3	473.9	304.7	246.5	356.4	229.1

(1) Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 5.6. Analyses of Cabernet Sauvignon wines produced in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
	Alcohol (%)					
2007/08	12.92	13.37	12.81	12.46	12.85	12.72
2008/09	13.08	14.24	14.31	13.83	14.21	13.70
	pH					
2007/08	3.64	3.59	3.72	3.57	3.63	3.55
2008/09	3.57	3.58	3.71	3.48	3.60	3.67
	Total acidity (g/L)					
2007/08	5.16	5.77	4.50	5.86	5.15	5.84
2008/09	6.58	6.72	6.39	7.11	6.91	7.22
	Volatile acidity (g/L)					
2007/08	0.17	0.10	0.25	0.17	0.15	0.16
2008/09	0.12	0.10	0.10	0.20	0.15	0.17
	Reducing sugar (g/L)					
2007/08	1.53	1.43	1.05	1.05	1.09	1.02
2008/09	1.05	1.09	0.85	0.78	1.43	1.22
	K					
2007/08	1040	786	1505	954	1355	1600
2008/09	1362	1389	1660	1306	1714	2003
	Malic acid (g/L)					
2007/08	1.20	1.80	0.77	2.38	1.56	2.14
2008/09	2.18	2.45	2.71	2.58	2.95	3.49
	Polyphenols (mg/L)					
2007/08	1449	1037	1125	1075	1157	975
2008/09	1529	1433	1465	1103	1461	1273
	Anthocyanin (mg/L)					
2007/08	298	276	243	302	273	287
2008/09	283	248	242	240	236	237
	Colour (420 nm)					
2007/08	2.3	2.3	1.7	1.5	1.7	1.9
2008/09	4.3	4.4	3.5	2.7	3.0	2.3
	Colour (520 nm)					
2007/08	3.6	3.7	2.0	1.7	1.8	2.5
2008/09	6.6	6.8	5.0	4.4	4.2	3.0

(1) Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.
(2)

Table 5.7. Analysis of Cabernet Sauvignon wines produced in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	**Locality**					
	Wellington			**Philadelphia**		
	WNI[(1)]	**WSD**	**WDD**	**PNI**	**PSD**	**PDD**
	Volatile acidity (g/L)					
2007/08	0.22	0.12	0.37	0.25	0.23	0.27
2008/09	0.14	0.12	0.16	0.22	0.19	0.20
	Total acid (g/L)					
2007/08	5.34	5.77	4.68	5.70	5.94	5.37
2008/09	6.14	6.28	6.09	6.32	6.28	6.54
	Malic acid (g/L)					
2007/08	1.36	2.16	0.68	2.65	2.81	2.10
2008/09	2.50	2.92	7.00	2.85	3.41	4.10
	Fructose (g/L)					
2007/08	1.07	0.96	1.03	0.96	0.95	1.22
2008/09	1.41	1.45	1.59	1.40	1.54	1.63
	Ethanol (%)					
2007/08	12.20	13.24	12.72	13.82	12.76	13.24
2008/09	13.05	14.05	14.17	12.98	13.63	13.10

[(1)] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

Table 5.8. Sensorial evaluation of Cabernet Sauvignon wines produced in six experiment plots at two localities in the Swartland region during the 2007/08 and 2008/09 seasons.

Season	Locality					
	Wellington			Philadelphia		
	WNI[1]	WSD	WDD	PNI	PSD	PDD
			Wine colour (%)			
2007/08	63.3	65.9	35.0	31.5	26.0	51.6
2008/09	92.2	93.1	68.6	68.5	65.8	38.7
			Fresh vegetative character (%)			
2007/08	44.3	45.0	36.6	31.0	29.5	55.4
2008/09	47.5	35.4	41.7	29.8	32.5	42.0
			Cooked vegetative character (%)			
2007/08	32.4	35.6	31.9	24.4	36.8	29.5
2008/09	18.5	33.9	14.9	21.6	27.3	32.4
			Berry intensity (%)			
2007/08	56.8	46.0	33.2	43.9	34.6	46.5
2008/09	48.3	48.9	47.3	46.0	47.6	25.8
			Spicy intensity (%)			
2007/08	31.3	28.8	27.7	22.1	24.3	19.1
2008/09	23.1	23.7	26.8	20.8	28.5	16.1
			Acidity (%)			
2007/08	50.2	59.7	52.2	54.4	57.0	58.8
2008/09	58.0	56.8	58.1	61.2	62.6	59.2
			Body (%)			
2007/08	45.7	48.8	24.2	25.9	23.8	38.8
2008/09	57.5	62.7	56.9	48.3	43.6	35.4
			Astringency (%)			
2007/08	29.2	34.3	21.4	28.8	17.5	25.4
2008/09	30.7	32.8	33.9	36.2	28.3	29.7
			Overall quality (%)			
2007/08	52.9	51.5	30.0	35.6	31.4	44.9
2008/09	59.8	65.5	53.1	50.4	45.2	33.3

[1] Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

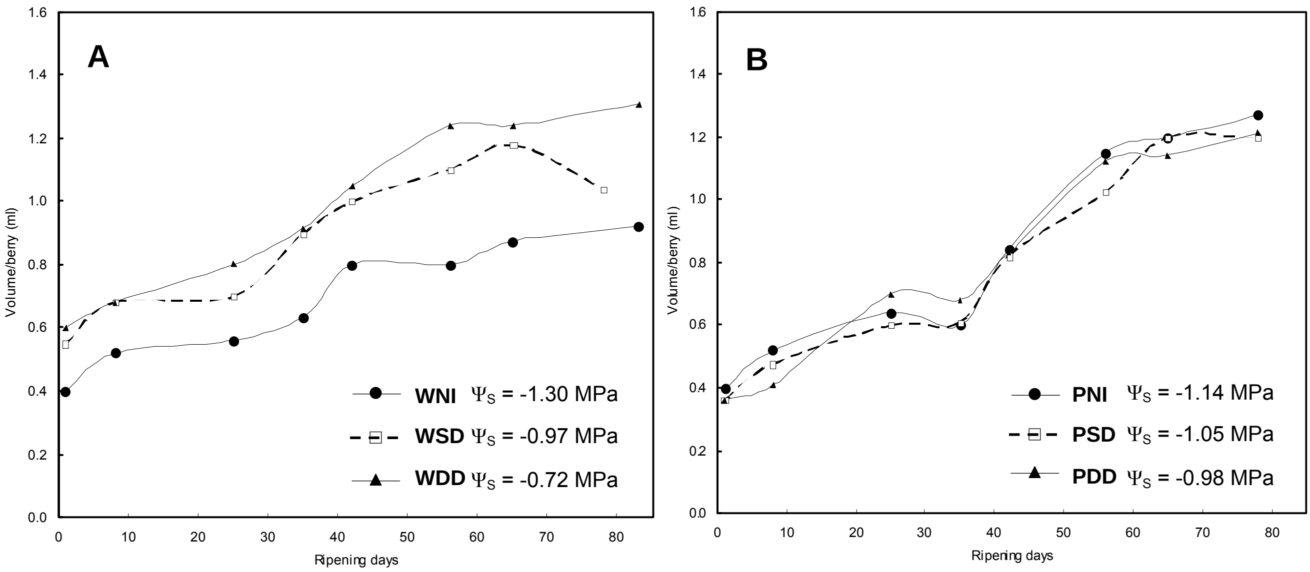

Figure 5.1. Berry volume of Cabernet Sauvignon near (A) Wellington and (B) Philadelphia in the 2007/08 season. Refer to Table 3.2 for description of plots. “W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

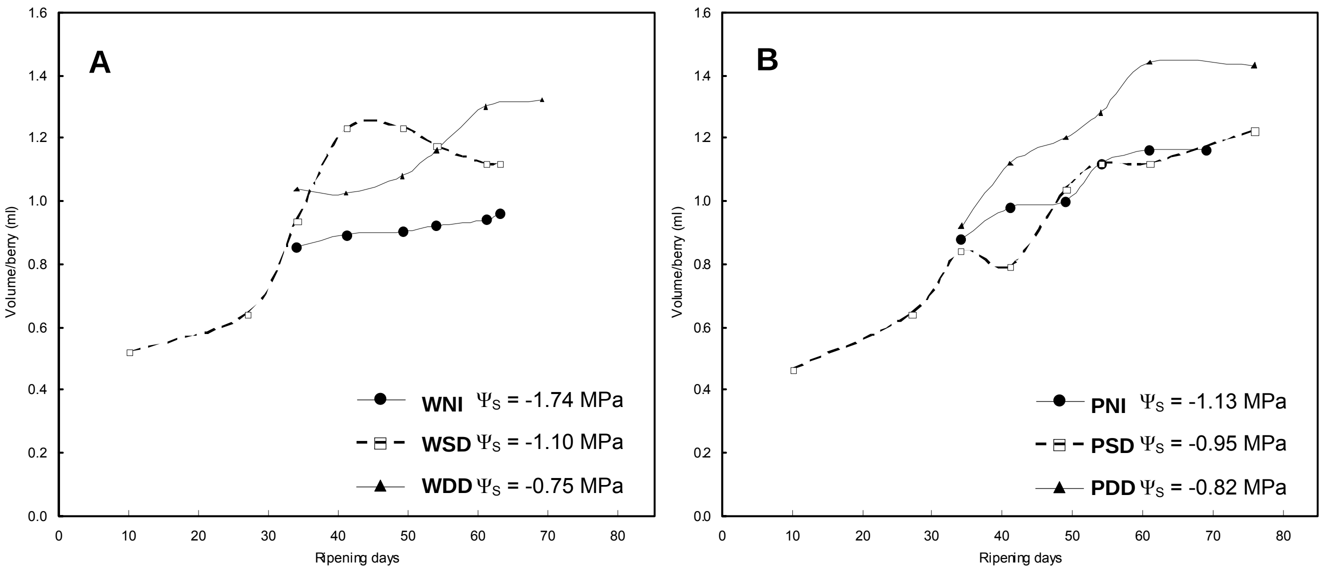

Figure 5.2. Berry volume of Cabernet Sauvignon near (A) Wellington and (B) Philadelphia in the 2008/09 season. Refer to Table 3.2 for description of plots. W” and “P” indicate Wellington and Philadelphia, respectively, whereas “NI”, “SD” and “DD” indicate non-irrigated, single line drip and double line drip.

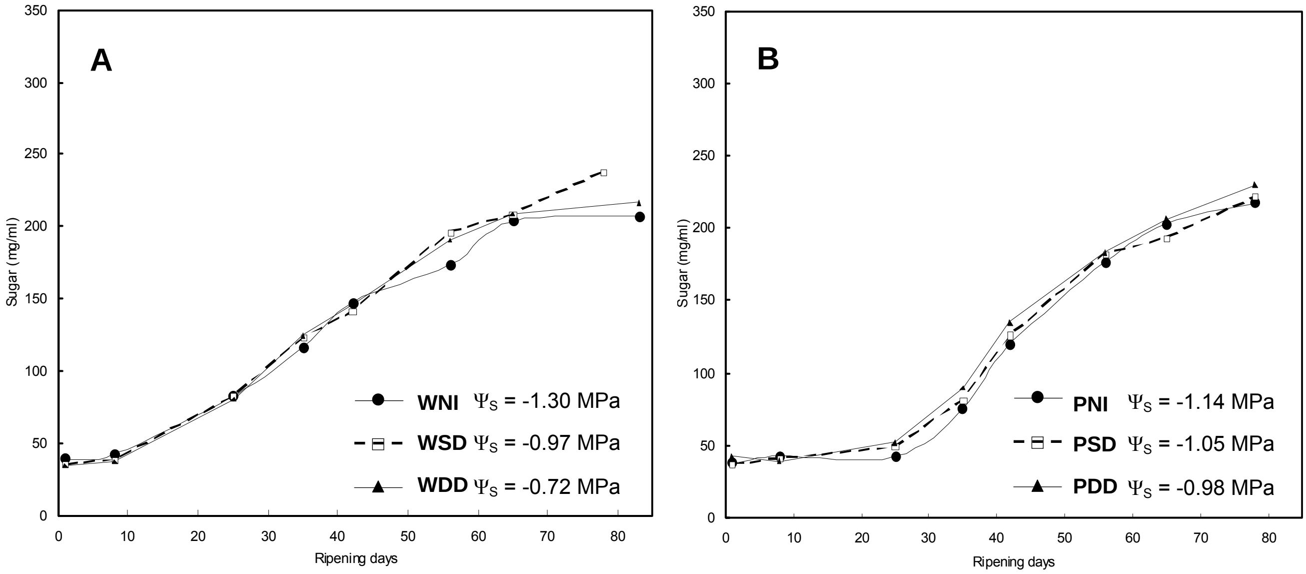

Figure 5.3. Sugar concentration in Cabernet Sauvignon berries near (A) Wellington and (B) Philadelphia in the 2007/08 season. Refer to Table 3.2 for description of plots. W" and "P" indicate Wellington and Philadelphia, respectively, whereas "NI", "SD" and "DD" indicate non-irrigated, single line drip and double line drip.

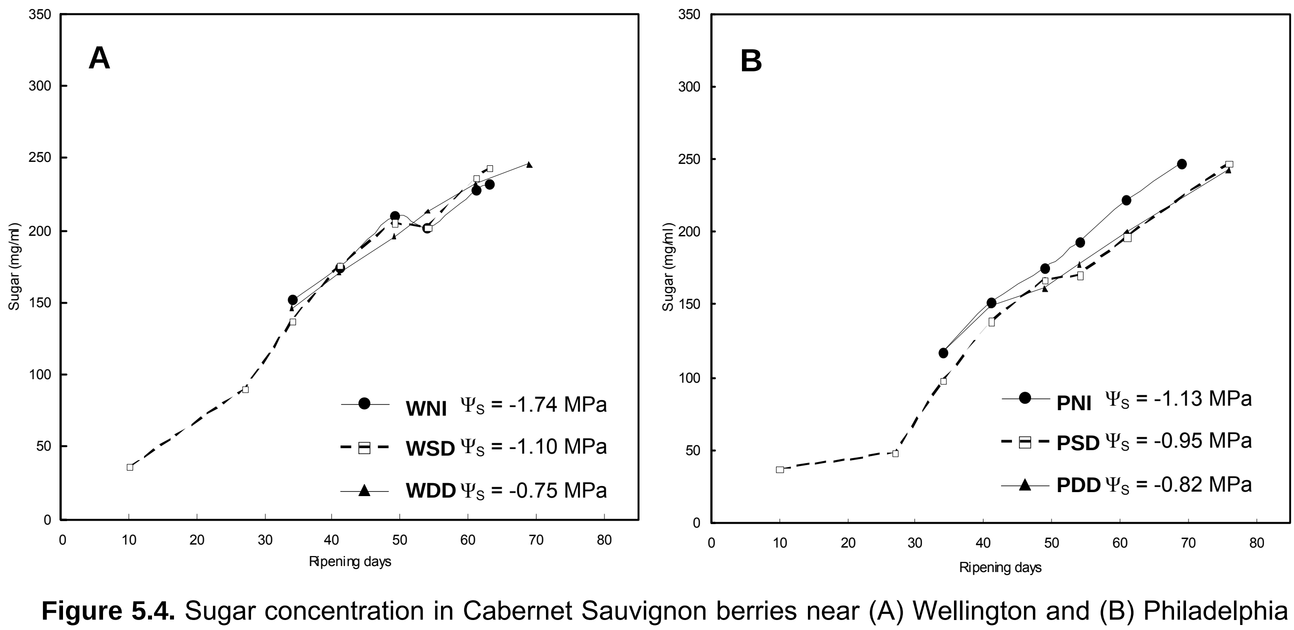

Figure 5.4. Sugar concentration in Cabernet Sauvignon berries near (A) Wellington and (B) Philadelphia in the 2008/09 season. Refer to Table 3.2 for description of plots. W" and "P" indicate Wellington and Philadelphia, respectively, whereas "NI", "SD" and "DD" indicate non-irrigated, single line drip and double line drip.

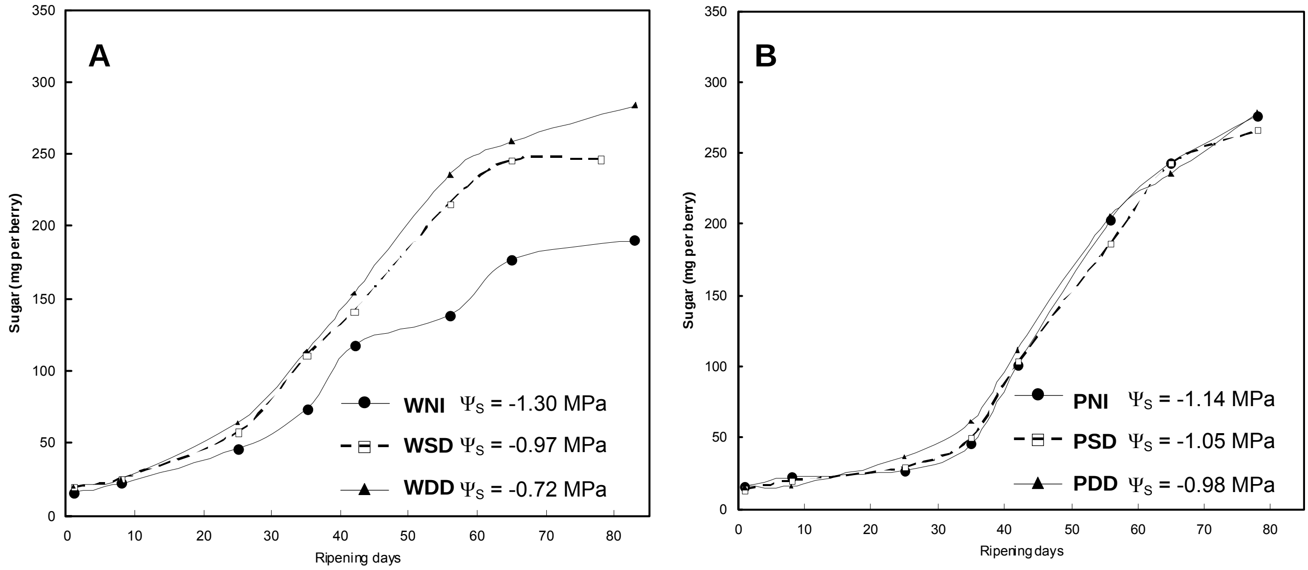

Figure 5.5. Sugar content in Cabernet Sauvignon berries near (A) Wellington and (B) Philadelphia in the 2007/08 season. Refer to Table 3.2 for description of plots. W" and "P" indicate Wellington and Philadelphia, respectively, whereas "NI", "SD" and "DD" indicate non-irrigated, single line drip and double line drip.

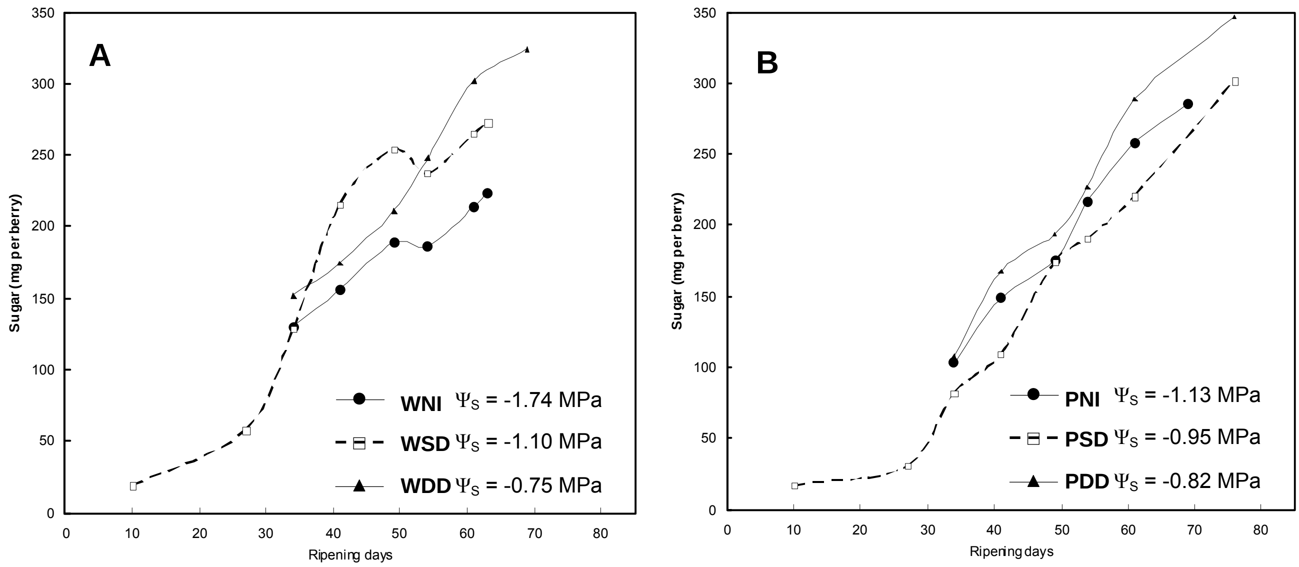

Figure 5.6. Sugar content in Cabernet Sauvignon berries near (A) Wellington and (B) Philadelphia in the 2008/09 season. Refer to Table 3.2 for description of plots. W" and "P" indicate Wellington and Philadelphia, respectively, whereas "NI", "SD" and "DD" indicate non-irrigated, single line drip and double line drip.

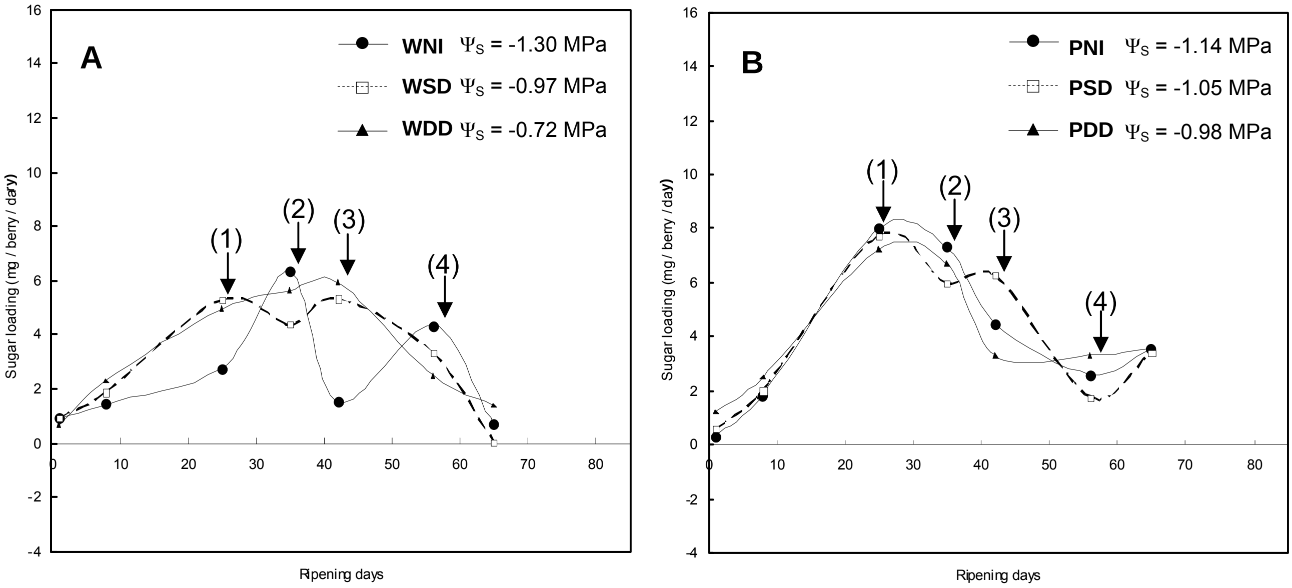

Figure 5.7. Sugar loading in Cabernet Sauvignon grapes near (A) Wellington and (B) Philadelphia in the 2007/08 season. Vertical arrows indicate 4 January (1), 14 January (2), 21 January (3) and 4 February (4) 2008, respectively. Refer to Table 3.2 for description of plots. W" and "P" indicate Wellington and Philadelphia, respectively, whereas "NI", "SD" and "DD" indicate non-irrigated, single line drip and double line drip.

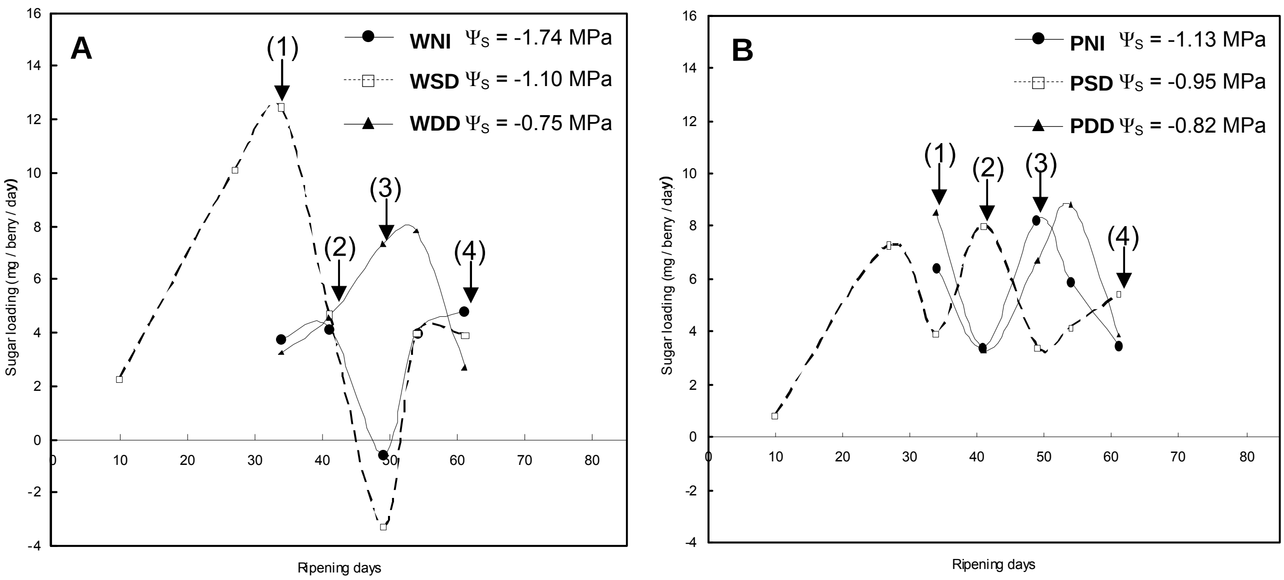

Figure 5.8. Sugar loading rate in Cabernet Sauvignon grapes near (A) Wellington and (B) Philadelphia in the 2008/09 season. Vertical arrows indicate 13 January (1), 20 January (2), 28 January (3) and 9 February (4) 2009, respectively. Refer to Table 3.2 for description of plots. W" and "P" indicate Wellington and Philadelphia, respectively, whereas "NI", "SD" and "DD" indicate non-irrigated, single line drip and double line drip.

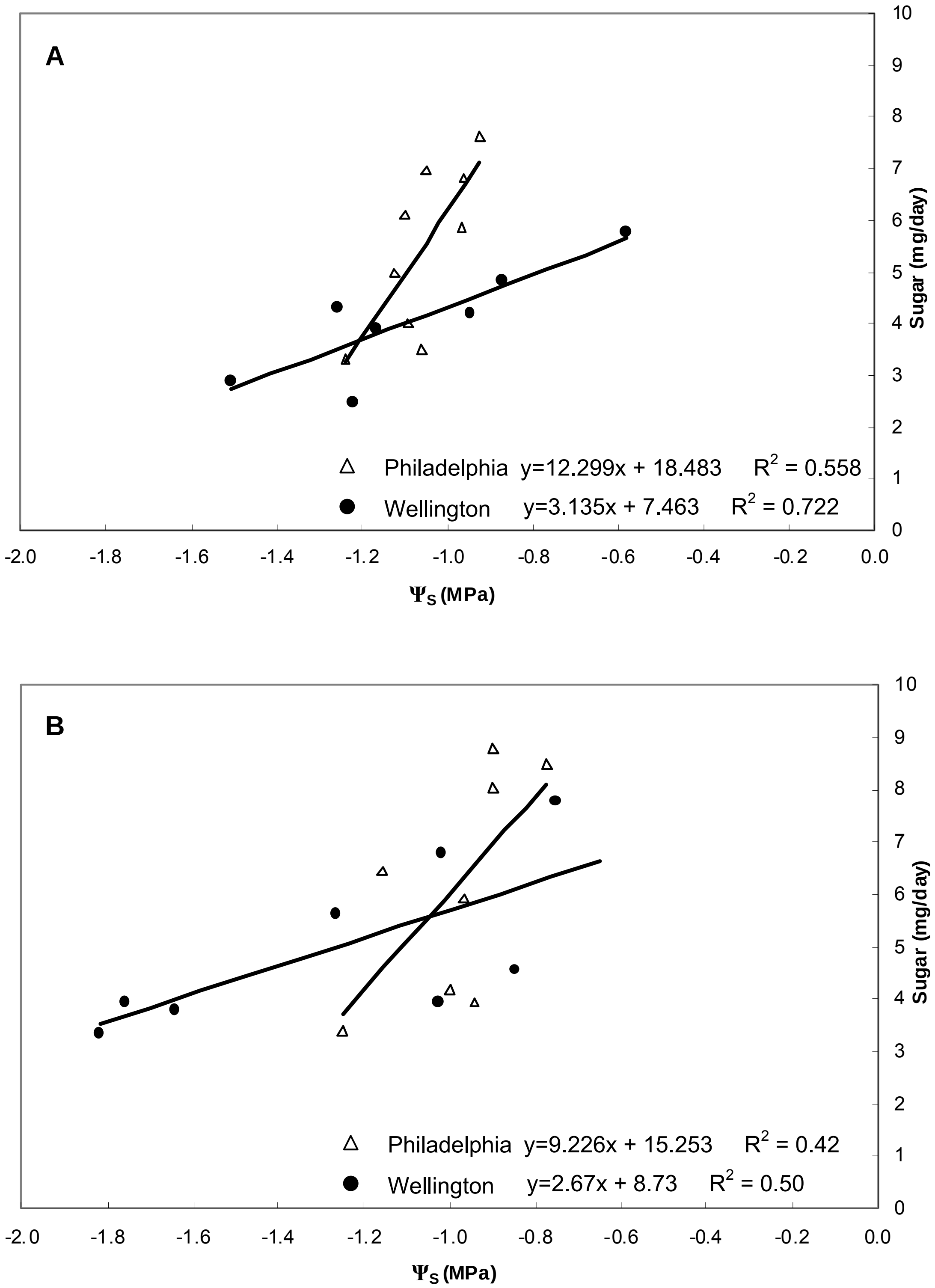

Figure 5.9. The relationship between sugar loading and stem water potential (Ψ_S) in Cabernet Sauvignon grapevines at two localities in the Swartland region during (A) the 2007/08 and (B) the 2008/09 season, respectively.

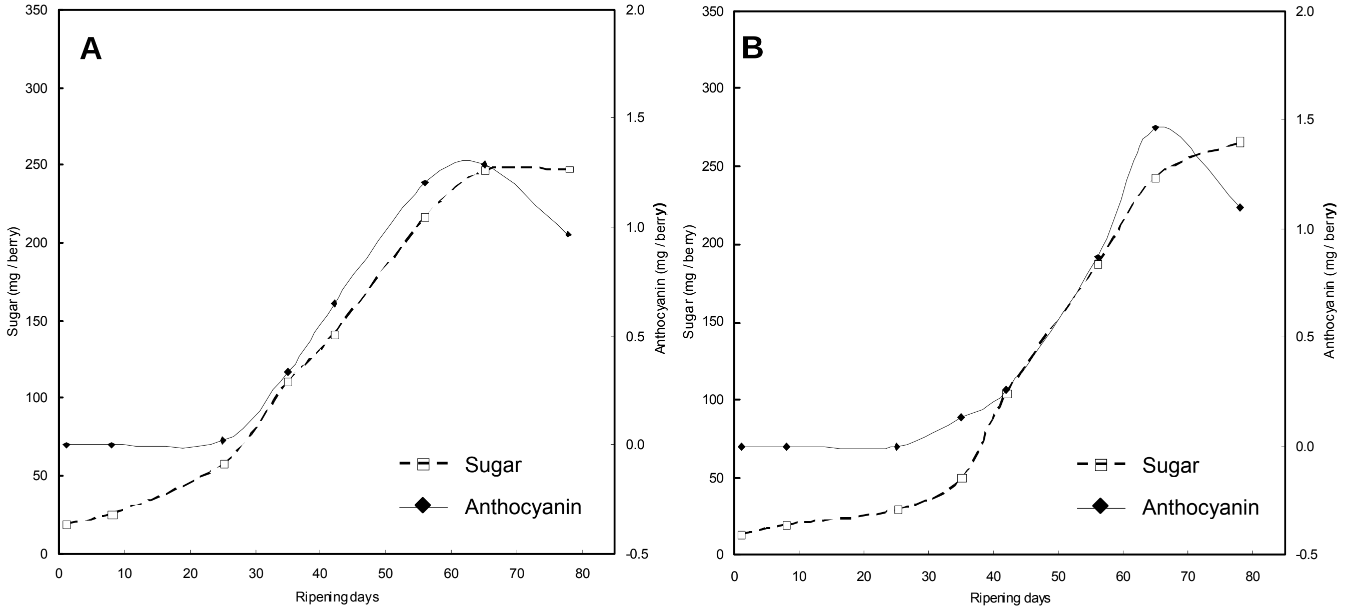

Figure 5.10. Sugar loading and anthocyanin biosynthesis in grapes produced by single line drip irrigated Cabernet Sauvignon grapevines in the 2007/08 season near (A) Wellington and (B) Philadelphia.

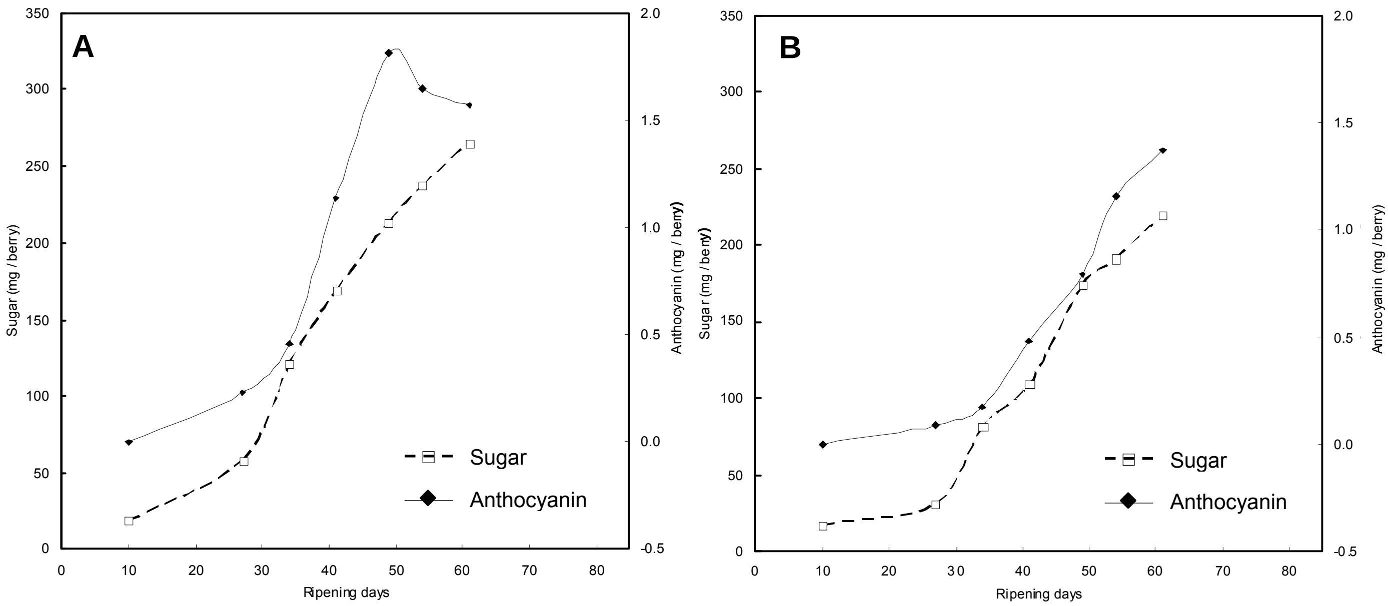

Figure 5.11. Sugar loading and anthocyanin biosynthesis in grapes produced by single line drip irrigated Cabernet Sauvignon grapevines in the 2008/09 season near (A) Wellington and (B) Philadelphia.

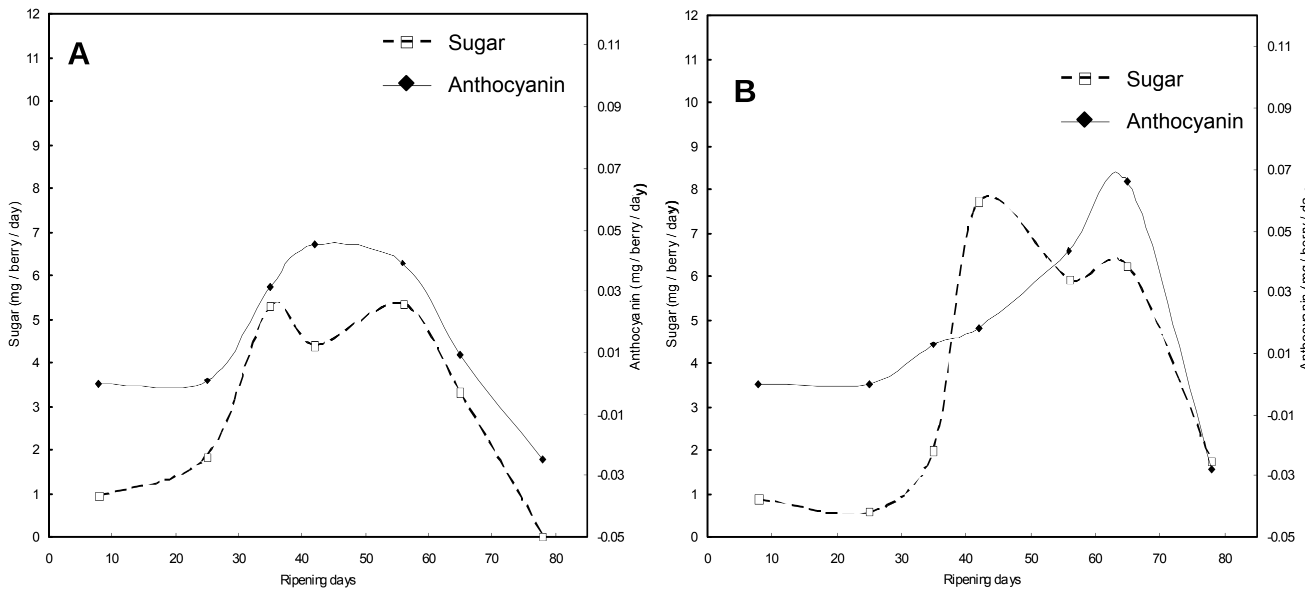

Figure 5.12. Sugar loading and anthocyanin biosynthesis rates in grapes produced by single line drip irrigated Cabernet Sauvignon grapevines in the 2007/08 season near (A) Wellington and (B) Philadelphia.

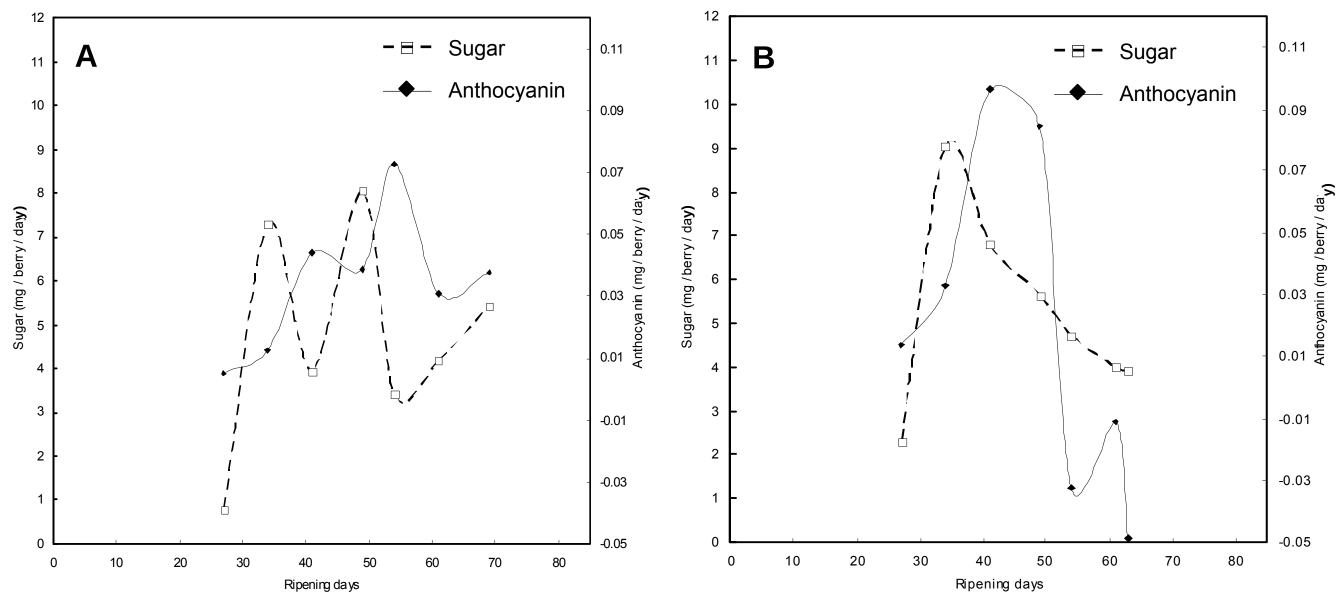

Figure 5.13. Sugar loading and anthocyanin biosynthesis rates in grapes produced by single line drip irrigated Cabernet Sauvignon grapevines in the 2008/09 season near (A) Wellington and (B) Philadelphia.

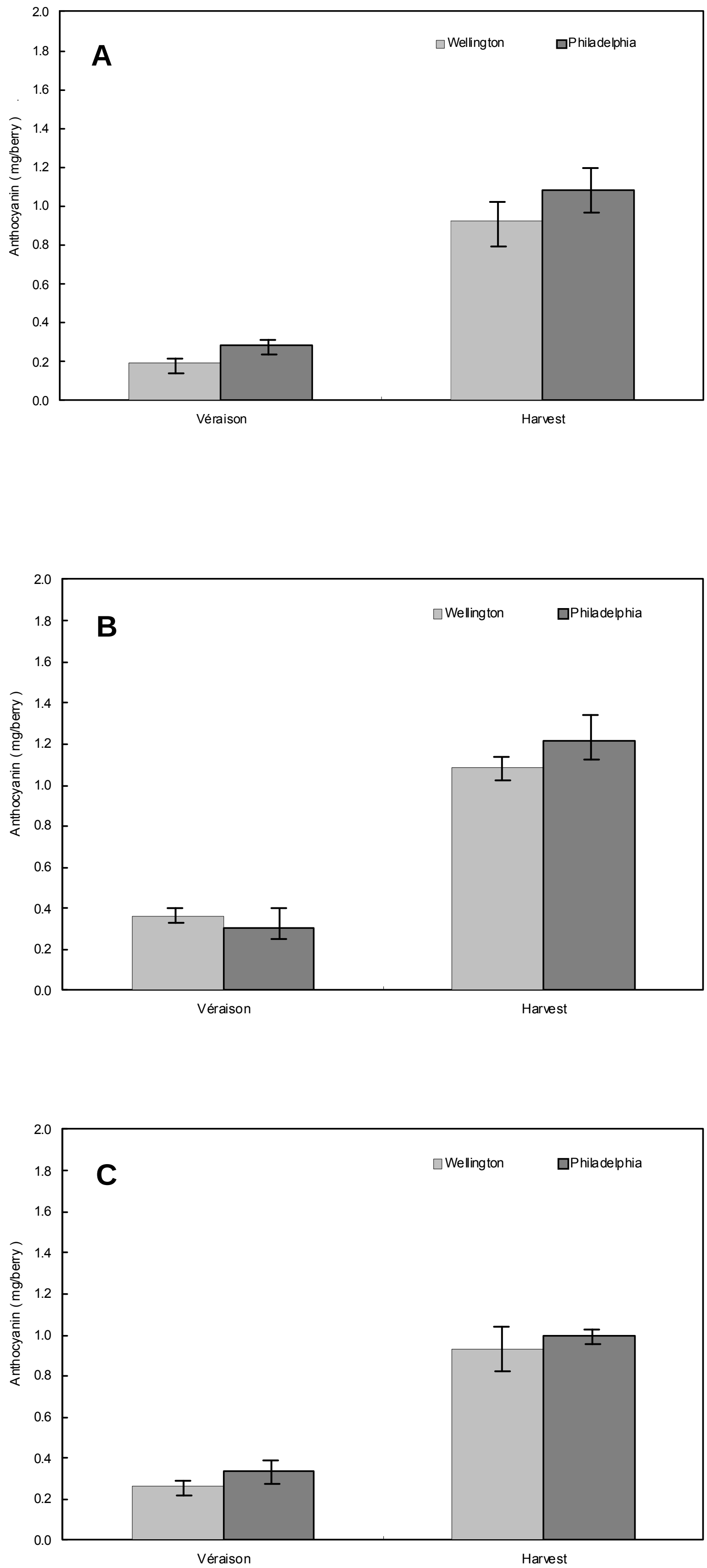

Figure 5.14. Total anthocyanin per berry at véraison and harvest, respectively, in grapes produced by (A) non-irrigated, (B) single line drip and (C) double line drip irrigated Cabernet Sauvignon grapevines at two localities in the Swartland region during the 200/08 season.

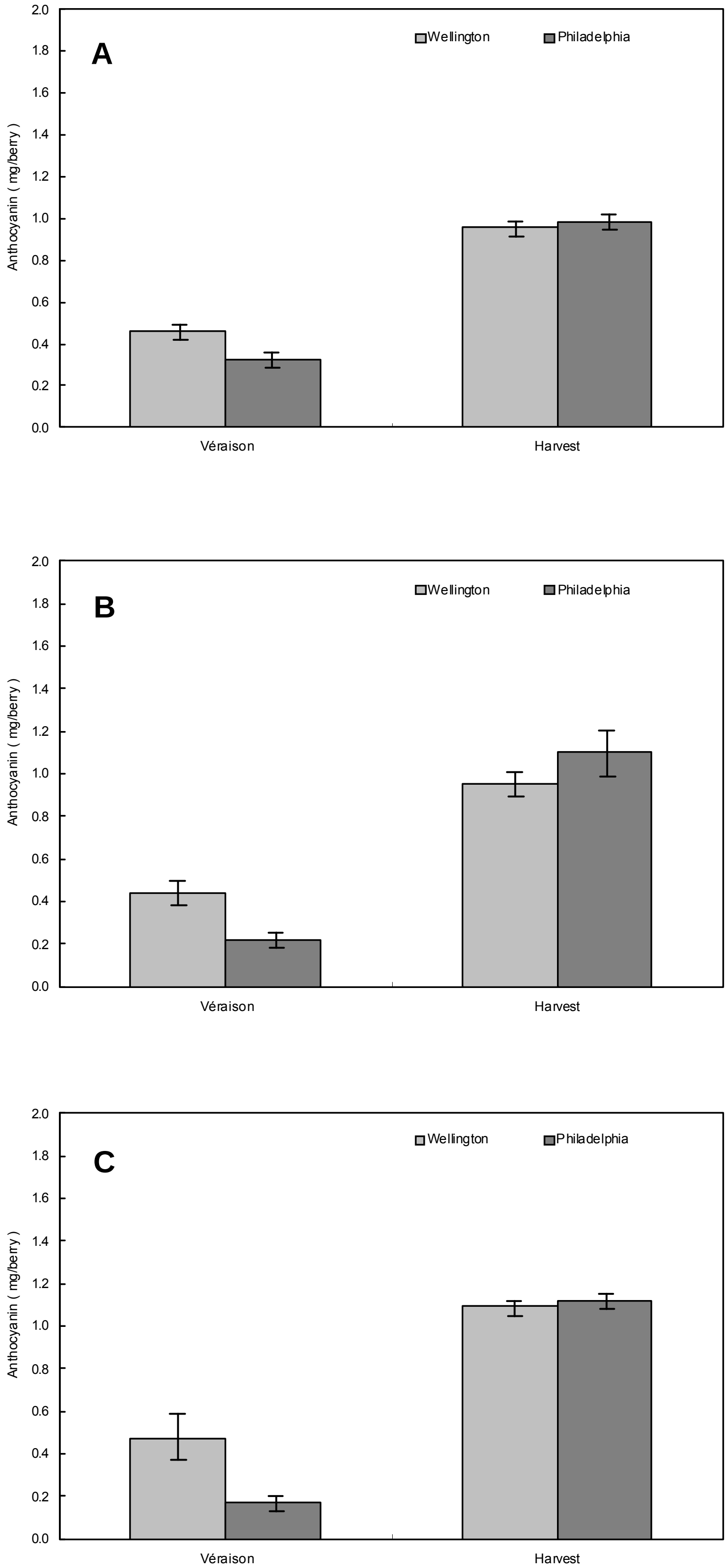

Figure 5.15. Total anthocyanin per berry at véraison and harvest, respectively, in grapes produced by (A) non-irrigated, (B) single line drip and (C) double line drip irrigated Cabernet Sauvignon grapevines at two localities in the Swartland region during the 2008/09 season.

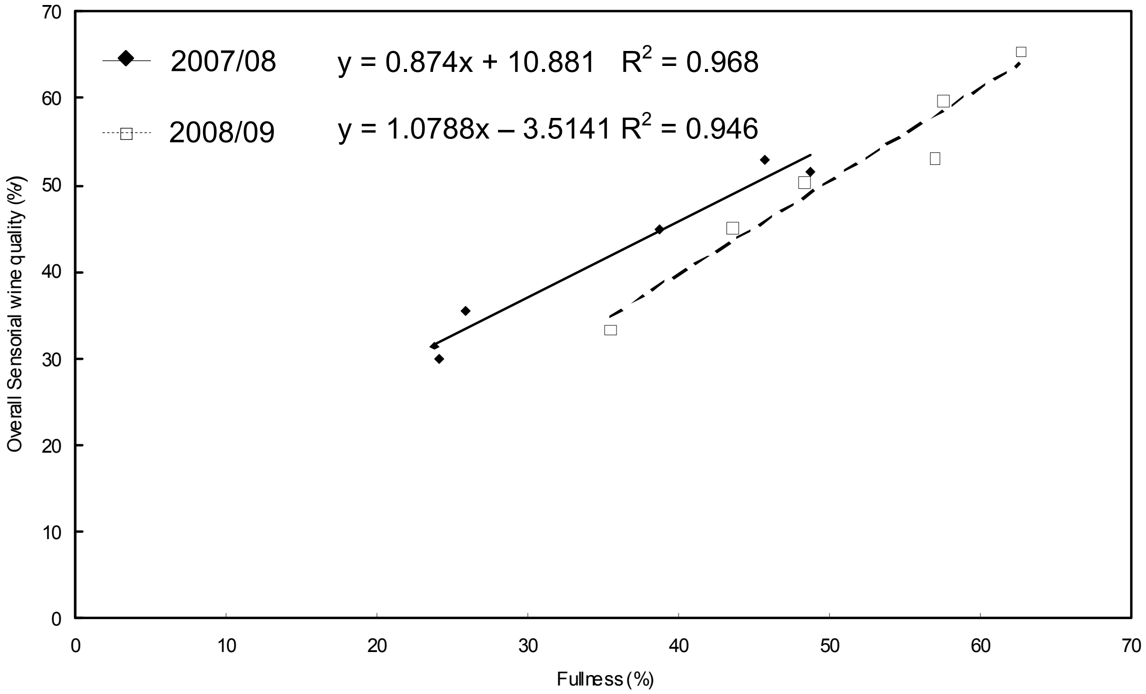

Figure 5.16. The relationship between wine sensorial quality and wine fullness in Cabernet Sauvignon wines in the Swartland region during two seasons.

Chapter 6

GENERAL DISCUSSION AND CONCLUSIONS

GENERAL DISCUSSION AND CONCLUSIONS

In the Coastal region of the Western Cape, proximity to the Atlantic Ocean plays an important role in describing the potential for viticultural cultivation. On a regional macro climatic scale, the Swartland region is generally classified as having a hot climate, where the temperature increases with distance from the ocean. As a result, climate varies on a meso scale. In this study, two distinct climatic regions in the Swartland were identified, namely Philadelphia and Wellington which are 12 km and 51 km from the Atlantic Ocean, respectively. Based on Mean February Temperature, Philadelphia was classified as having a moderate climate and Wellington as having a hot to very hot climate. This was confirmed by the Winkler Index, whereby Philadelphia and Wellington were Class III and Class V, respectively. The Heliothermal Index also confirmed the classification into two temperature classes. The Cool Night Index however, showed no difference between the two localities.

The soil chemical and physical properties were comparable at the two sites. Therefore, these factors could be eliminated as reasons for causing different grapevine responses. Due to the similarity of soils at the two sites, root densities were comparable. Although the soil water holding capacities of the two soils were comparable, it does not rule out the possibility that the volume of irrigation water applied will influence grapevine functioning. When the climate is warmer, irrigation could have a more prominent effect on grapevine response than under moderate conditions.

Irrigation volumes induced different grapevine water constraints in terms of midday water potential. Stem water potential showed to be a more sensitive indicator of grapevine water status compared to leaf water potential, and was linearly related to the soil matric potential. Water constraints at Wellington could be classified as being mild to moderate and strong in the irrigated and non-irrigated grapevines, respectively. In the moderate climate at Philadelphia only mild water constraints occurred, irrespective of water application. Therefore, grapevines closest to the ocean tended to experience less water constraints over the course of the day compared to ones further inland. This effect could become more pronounced as the season progresses, not only due to the changes the atmospheric conditions, but also as a result of drier soil. The effect of the warmer climate on grapevine water constraints could be modified by irrigation, but in the moderate climate, irrigation had almost no effect. This showed that the grapevine water status was directly dependent and related to soil water status and climate. Climate appeared to be the driving factor in determining water constraints at Philadelphia, whereas the soil water content played a more prominent role at Wellington. These results indicated that the measurement of diurnal leaf water potential cycles at different phenological stages is required to fully understand the effect of the climate and soil on the grapevine water status.

Warmer sites have a higher evaporation and transpiration demand compared to cooler climates, therefore placing a greater demand on the plant available soil water. Grapevines in the warmer climate at Wellington required the application of water to alleviate severe constraints, as they seem to function optimally under moderate constraints. Optimal grapevine functioning means the vegetative and reproductive growth of the grapevine is balanced. This was evident in the moderate constraint conditions, namely single drip line at Wellington and non-irrigated at Philadelphia. Therefore, the climate is an important consideration in irrigation scheduling.

The general vegetative growth response to water application and seasonal temperature differences showed that shoot length, leaf area and cane mass increased with an increase of water availability and cooler climate. Moderate water constraints could balance vegetative and reproductive growth, and limit shoots to the desired length of *ca.* 1.2 m recommended for producing and ripening optimal quality Cabernet Sauvignon grapes. Irrigation and lower temperatures at Philadelphia tended to increased berry size, whilst severe water constraints and warmer temperatures, which limited optimal grapevine functioning, had the opposite effect at Wellington. Consequently, yield increased with a decrease in grapevine water constraints induced by the application of water.

Higher temperature, and the increased heat summation units, directly influenced the phenological ripening of the grapevine. Bud burst of grapevines near Wellington tended to occur about two weeks before Philadelphia. Berry ripening and sugar loading also occurred earlier at Wellington. The harvest date seemed to be water constraint related. At each of the two sites, grapes experiencing moderate water constraints reached the desired ripeness level of 24˚B first. This suggested that water constraints at the two localities influenced the photosynthetic activity of the grapevines. Results from this study confirmed that the grapevine water status influenced berry volume and the dynamics of berry ripening.

More moderate climate seemed to limit and, to some degree, retard the sugar accumulation in the berries because minimal water constraints experienced by the grapevine resulted in excessive vegetative growth. At Wellington, the desired sugar level could not be reached probably because of the inhibition of photosynthesis resulting from higher water constraints and temperature. Sugar concentration (mg/ml) was the highest in plots where moderate water constraints occurred, as balanced grapevines had the highest sugar accumulation, probably due to optimum photosynthesis and carbohydrate utilization. Vegetative growth was a sink to the detriment of sugar loading. It was clear that ˚B increased throughout the season. However, this increase was not always as a result of sugar loading, but could also have been due to a concentration effect because of smaller berries caused by water and temperature constraints. Therefore berry volume, rather than Balling, seemed to be a more reliable indicator of grapevine functioning than Balling.

The berry sugar content of grapevines in most of the plots reached the plateau of sugar loading. The only exception was where grapevines growing near Philadelphia were irrigated by means of a single drip line. Anthocyanin biosynthesis in the grapes, as quantified on a per berry basis, showed that sugar loading and anthocyanin biosynthesis were co regulated, with anthocyanin biosynthesis reaching its plateau when the sugar content per berry was between 200 mg/mL to 220 mg/mL. Grapes with the most colour at véraison were produced under moderate water constraints, namely single drip line irrigation near Wellington and non-irrigated conditions near Philadelphia. However, at harvest, grapes from the cooler climate tended to have the more intense colour and higher phenolics. This was probably because anthocyanin biosynthesis was favoured by the cooler temperatures of approximately 20˚C closer to the ocean.

The best sensorial wine colour was produced from grapes where moderate water constraints induced balanced vegetative and reproductive growth, allowing for optimal exposure to sunlight and grapevine functioning required for optimal ripening of all berry components. Deficit irrigation tended to increase sensorial wine colour intensity, as well as the fullness of the wines. This may have been caused by the indirect effect of reduced vegetative growth which could have improved bunch micro climate and, consequently stimulated anthocyanin biosynthesis. The concentrated metabolites could also have contributed to the increased sensorial wine fullness. Moderate water constraints, irrespective of climate, produced the best quality wine in terms of classical sensorial evaluation. This trend was in agreement with previous studies which showed that restricted irrigation inducing moderate water constraints can enhance wine colour and quality. The sensorial wine quality increased with an increase in fullness, which in turn increased with the optimal functioning of the grapevine.

Irrespective of climate, water was shown to be the primary factor affecting grapevine functioning on a vegetative and grape berry level in the Swartland region. It can be concluded that vineyards in the warmer areas in this particular region will require some irrigation to alleviate severe water constraints and allow moderate water constraints favourable for balanced grapevine growth. In contrast, grapevines in the deeper soils in the cooler areas might require no irrigation since the climate-soil interaction can result in moderate water constraints which could be favourable for optimal plant functioning. However, this does not negate the importance of canopy management practices to obtain specific cultivar and wine styles in the different climatic regions in the Swartland region.